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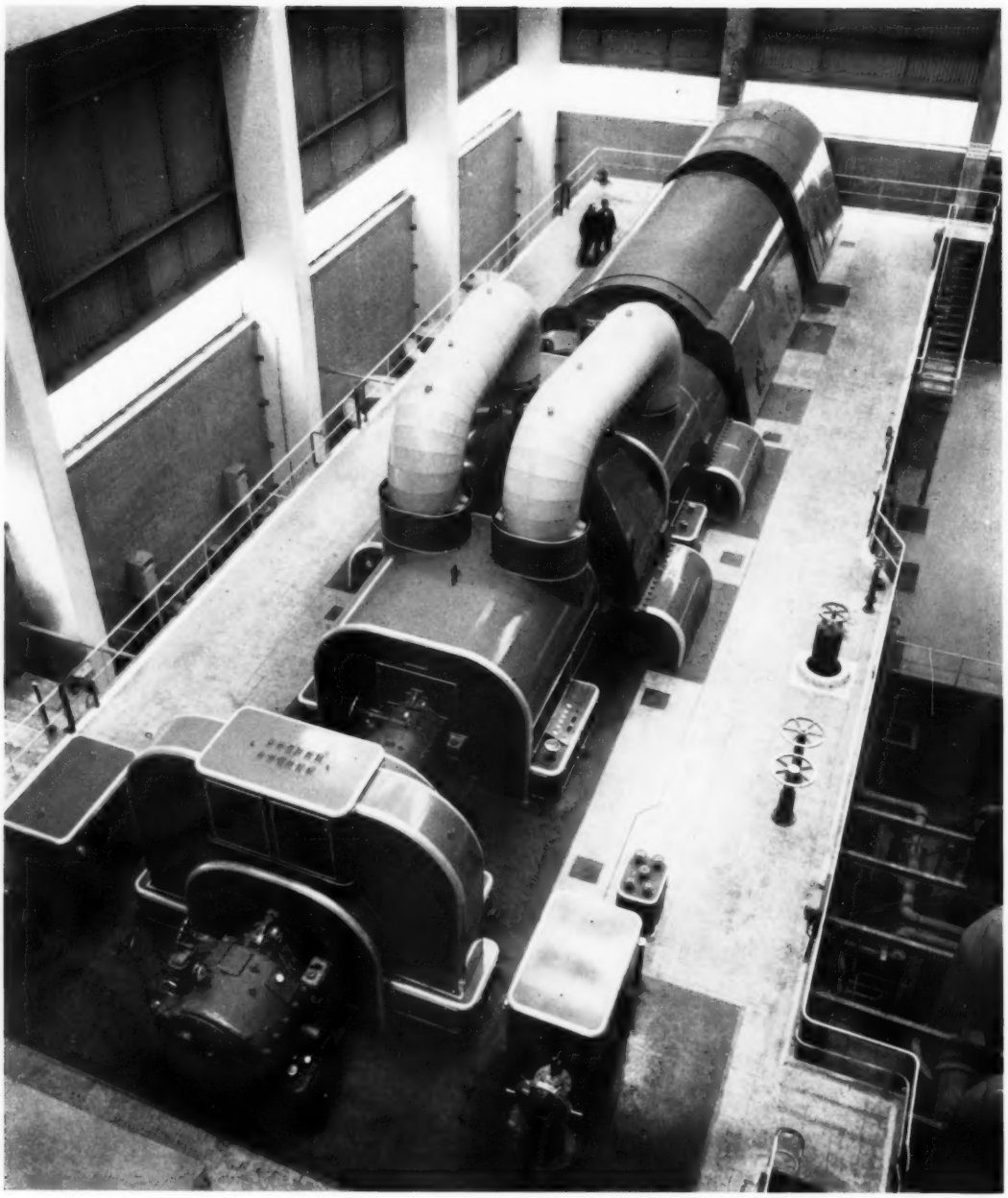


One of four 100 *MW 'English Electric' turbo-alternator sets in the Willington 'A' power station of the Central Electricity Generating Board. The alternator of this set, No.* 2, *has direct-cooled stator and rotor conductors*

The Development of Direct Gas Cooling as Applied to Large Turbo-Alternators

By K. HOBLEY, M.Eng., Grad.I.E.E., Machine Design Department, Stafford.

This article refers particularly to the application of direct gas cooling to the No. 2 alternator recently installed at the Willington 'A' power station of the Central Electricity Generating Board.

POST-WAR DEVELOPMENT in all spheres of engineering and science has been far more intense than in the years preceding the war. In the field of electrical power generation the immediate post-war situation was one of consolidation, involving the production of machines of established design and proved performance to meet the increased demand for power, and to replace old, outdated and inefficient plant.

While production was proceeding on generators of conventional designs the principle of hydrogen cooling was introduced into Britain, towards the end of the last decade, to enable larger outputs to be obtained from existing frame sizes. However, it was realised that there would soon be a demand for single-unit generators having outputs far in excess of the limits existing on conventional machines, even with the adoption of hydrogen cooling.

The physical limits of machine size are determined by a number of factors, the most serious of which is the maximum size of stator which it is permissible to transport, and in order to obtain further increases in output from the maximum existing frame sizes it was obvious that a completely new approach was required to enable any remarkable degree of uprating to be achieved.

BASIC DESIGN CONSIDERATIONS

An increase in hydrogen pressure inside a conventional hydrogen cooled alternator from $\frac{1}{2}$ p.s.i.g., the basic pressure for the early machines installed, to 15 p.s.i.g., enables approximately 10% extra output to be obtained, assuming the short-circuit ratio to remain constant. A further 7% increase is possible by employing a gas pressure of

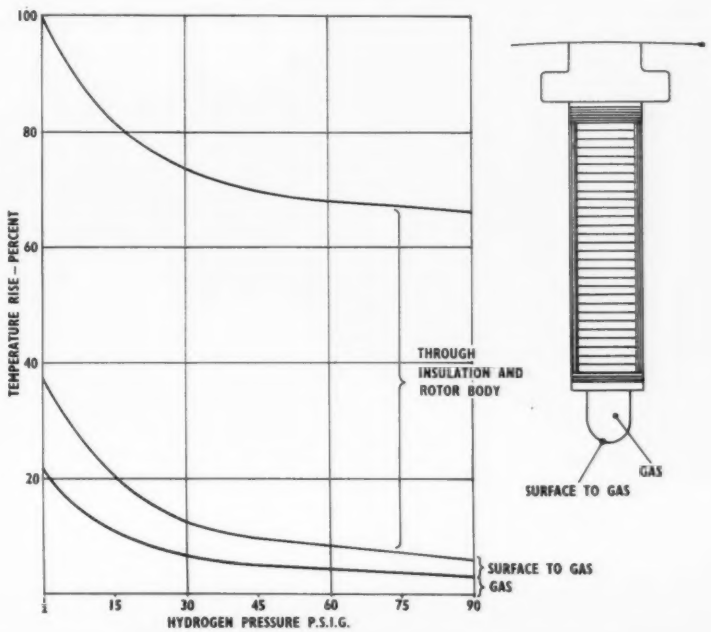


Fig. 1.—The components of temperature rise for a conventional rotor

30 p.s.i.g., but raising the gas pressure beyond this does not allow any significant additional output.

The fundamental limitations on increasing the output from an electrical machine are twofold, magnetic and thermal. Since the magnetic circuit is dependent on the permeabilities of the materials used, and no great improvement is possible in this field, particularly in the case of the rotor forging, which is the most influential item, it is obvious that the trend of development must be towards more efficient means of cooling both the rotor and the stator.

Investigation into Cooling Problems

It is well known that in conventional machines, where the cooling is effected by radial ducts in the stator core, and sub-slots or axial ventilation ducts in the steel of the rotor, the temperature gradients in the insulation and in the iron account for the greater part of the temperature rise. Fig. 1 shows the relative temperature gradients in the component parts of a conventional rotor, together with the effect of increasing gas pressure. The obvious aim of any development therefore was to eliminate the largest barriers to heat flow, namely the insulation and steel temperature gradients, to decide a policy for the cooling of the active components and to devise means of carrying this out.

Many different schemes were considered and the merits and shortcomings of each carefully studied.

The general principle decided upon was direct cooling of the current-carrying conductors, using hydrogen as the cooling medium. Liquid cooling of the stator was rejected for the first stage in the development since it was found practicable to obtain the required increase in output by using gas only, avoiding the additional complication of two separate cooling media. Later stages in the development of cooling systems are concerned with the use of liquid cooling for the stator winding where, in the further raising of unit sizes, the small saving in stator weight resulting from the much improved thermal properties is of great value. Fig. 2 shows the relative increases in current carrying capacity possible with increasing gas pressure for conventional and direct-cooled machines.

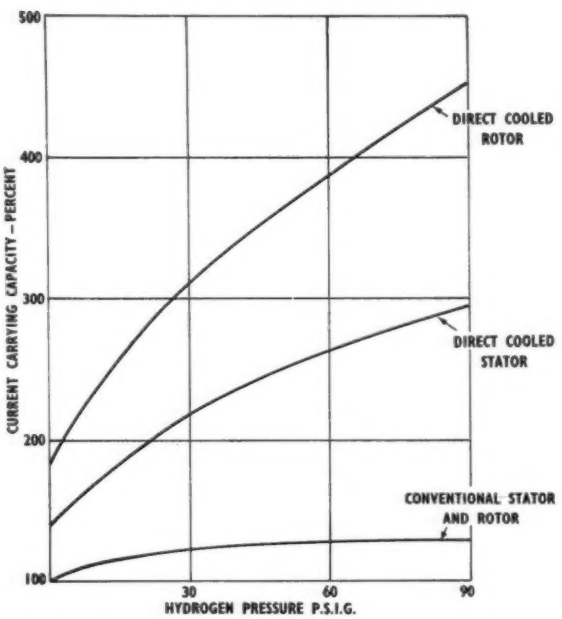


Fig. 2.—The variation of current carrying capacity with hydrogen pressure

The principles of ventilation for the active parts of the completely direct gas cooled design of turbo-alternator were developed on the following lines.

Rotor Winding

Hollow rectangular copper was chosen for the conductors, with axial ventilation of the slot portion from each end discharging into the 'air gap' through radial circular holes in the centre region of the rotor, the copper used being of the silver-bearing hard drawn type in order to reduce to a minimum the possibility of copper distortion. In order to keep down the hot-spot temperature of the longer coils to acceptable figures it was decided to separate the ventilation of the end-winding portions of all but the two inner coils from that of the slot portion, and arrange for the end-winding discharge gas to be conducted through axial holes in the coil end and separated from the inlet gas by means of steel extension forgings shrunk on to the

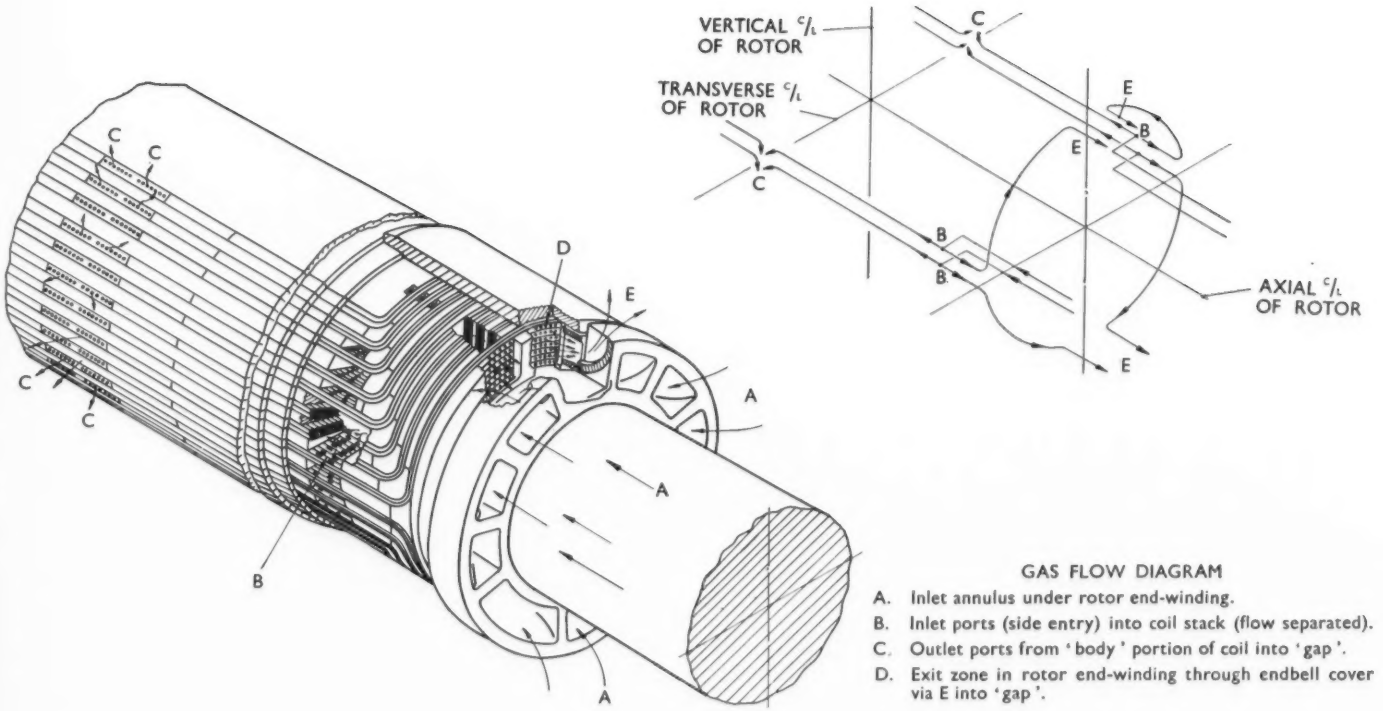

VERTICAL ℄ OF ROTOR
TRANSVERSE ℄ OF ROTOR
AXIAL ℄ OF ROTOR
C
E
B
D
A
GAS FLOW DIAGRAM
A. Inlet annulus under rotor end-winding.
B. Inlet ports (side entry) into coil stack (flow separated).
C. Outlet ports from 'body' portion of coil into 'gap'.
D. Exit zone in rotor end-winding through endbell cover via E into 'gap'.

Fig. 3.—Typical arrangement of direct-cooled rotor winding, with diagram showing ventilation paths

rotor shaft ends, outboard of the endbell covers. A special feature of the inlet ports to the hollow conductors is the adoption of side entry so that there would be no restriction on the gas intake should any slight malalignment of the conductors develop during subsequent service operation. Fig. 3 shows a typical arrangement of the construction, the line diagram illustrating the ventilation paths.

Stator Coils

A high-voltage stator coil precludes the use of any system other than end to end ventilation, owing to the difficulty of providing adequate electrical creepage paths in the embedded portion. Further, as in all alternating current machines, it is essential to sub-divide the conductor into separate small insulated strips to reduce eddy current losses to a minimum. The maximum size of duct possible in such laminations results in an excessive pressure drop, using hydrogen as the coolant, and it is therefore necessary to use thin-walled phosphor bronze tubes to convey the cooling gas. The tubes are insulated from each other by a thin layer of resin-impregnated glass sleeving, the thickness of insulation between the phosphor bronze tubes and the conductor being kept to a minimum to reduce the temperature gradient from gas to copper to as small a value as possible. This, while not sufficiently small to ignore, can be kept down to a small percentage of the total temperature gradient between the hot spot in the copper and the cool gas.

Stator Core

The necessary adoption of axial cooling for the stator coils was fortunate so far as the ventilation of the stator core is concerned. Extraction of heat from the edges of insulated steel coreplates is far more effective than from the plate surface, and since a stator core is necessarily laminated transversely to reduce eddy current losses, axial ventilation of the stator core is more efficient than the usual radial method. In addition, by having both the stator core and coils ventilated from end to end, the temperature difference between the stator copper and the core steel can be kept to a minimum.

Hydrogen Blower and Blower Drive

The next problem was to devise means of circulating the required quantity of coolant to extract the heat. Due to the very restricted inlet and outlet conditions a direct shaft-mounted fan is comparatively inefficient, besides which the synchronous speed of 3,000 r.p.m. is too low for a good aerodynamic design. Further, a shaft-mounted blower would require a considerable increase in shaft length, thereby seriously reducing the critical speed which is an important factor in the design of large units. A high-speed axial-flow blower is ideal for the duty required, particularly as its size is such that it can readily be mounted in the stator frame, at least in the case of machines up to about 300 MW.

Various methods of drive were considered in detail, the most attractive being the inclusion of an extra pinion in the exciter gearbox. The usual practice of the Central Electricity Generating Board, and most other authorities concerned with large generating plant, is to use shaft driven exciters which run at about 750 r.p.m. A gearbox is therefore necessary, and the extra cost and complication of providing this box with an additional take-off at the required speed, in the range of 7,000 to 9,000 r.p.m., are very small.

There were, however, problems in the design of the drive between the blower and the gearbox to allow for differential movement between the two components arising from thermal and other effects. Considerable development work was carried out in conjunction with D. Napier & Son Ltd on the drive assembly, including long-term tests on a full-size prototype, and the blower itself was developed by The English Electric Company's Gas Turbine Division at Whetstone. The blower was designed with an overhung rotor in order to avoid having a bearing within the alternator frame.

Heat Transfer and Fluid Flow

Having decided the general basis of the design of the direct gas cooled alternator, the application of fundamental thermodynamic theory to the various coolant paths was investigated to determine the most satisfactory parameters for the duct size in the stator core and coils, and rotor coils. In parallel with this the Company's Machine Development Laboratory at Stafford was enlarged by the construction of a heat transfer rig to enable full-scale samples of stator and rotor coil sections to be tested in hydrogen. Tests of this nature were

intended to determine the heat transfer and flow characteristics of the components. This work confirmed various aspects of the basic theory.

Excitation Requirements and Open Circuit Characteristic

At this juncture it is appropriate to mention that the application of direct cooling to an alternator enables the temperature rise to be calculated with very much more accuracy than is possible with conventional cooling. In the latter case the possibility of variations in the thermal resistivity characteristics of the insulation requires the conventional machines to be designed with a greater margin of safety. It will be appreciated therefore that the estimation of the rotor excitation at full load has similarly to be more exact in the case of direct cooled alternators, and this in turn requires an accurate prediction of the open-circuit characteristic of the alternator.

While various methods of doing this have been used in the past for new designs of machines, and have given reasonable results, it was felt that these methods did not give results near enough to the actual test characteristics, comparable to the accuracy now possible in temperature rise calculations on direct cooled machines. In order to be able to produce a calculated characteristic which agreed almost exactly with the test characteristic, an investigation was carried out during the early stages of the development work on direct cooling, to evolve the most accurate means of determining the degree of magnetic saturation in the various parts of the magnetic circuit. These include stator core and teeth, rotor core and teeth, and air gap, including allowance for the leakage flux existing in the rotor, in parallel with the main gap flux.

A new method evolved for calculating the open-circuit saturation characteristic, based on a more fundamental and rigorous analysis of the saturation effects, when applied to a number of machines for which the test characteristics were available, gave extremely encouraging results. The new method was also used to predict the open-circuit characteristic of the first 'English Electric' 100 MW alternator, having conventional cooling, and the calculated figures in this case also were fully substantiated by the test results.

THE WILLINGTON 'A2' DIRECT-COOLED ALTERNATOR

Application of Direct Gas Cooling to a Prototype

The basic design of the first fully direct gas cooled alternators was for a rating of 100-120 MW, but it was apparent that this was not to be the limit for very long, and soon tenders were called for by the Central Electricity Generating Board for ratings of 200 MW, and later 275 MW. Technically the design of a single alternator of this capacity and larger was now possible with the application of direct gas cooling, but in order to acquire the necessary manufacturing technique in a design which was an innovation, and to gain early operating experience with this type of machine, permission was obtained from the C.E.G.B. to construct such a machine for installation in the No. 2 position at Willington 'A' power station to give an output of 100 MW. This power station was one of the first to be designed around sets of 100 MW capacity, with the alternators conventionally cooled at a normal gas pressure of $\frac{1}{2}$ p.s.i.g., but in the design of the No. 2 machine it was decided to employ a gas pressure of 30 p.s.i.g. to take real advantage of the potentialities of this method of cooling.

The change-over to a direct-cooled alternator also required the provision of a larger exciter, firstly on account of the reduced number of turns per pole as a result of the use of copper tube for the conductors, and secondly as a result of an increase in the total ampere-turns required for full-load excitation.

Results of Direct Cooling

The use of direct cooling in the extraction of the losses from a machine implies the ability to increase the current densities in the stator and rotor conductors, but it must also inevitably result in a reduction in frame size in order to enable the maximum benefits to be obtained. This is achieved by increasing the electrical loading, one of the two fundamental parameters in the design of an electrical machine, the other being the magnetic loading, which cannot be affected by the use of improved heat extraction methods since it is solely dependent on the magnetic characteristics of the materials used. These have not altered appreciably in

recent years. The only exception is the introduction of cold rolled oriented grain sheet steel for use in the stator core, but since the material as available at present is uni-directional in its properties, the advantage of increased permeability can only be utilised in the back of the stator core, the permeability in the teeth being similar to that of conventional hot rolled material. In any case, as stated earlier, the rotor forging is far the most important feature in the magnetic circuit, and its magnetic properties have naturally remained unchanged.

Increasing the electrical loading automatically results in an increase in the demagnetising effect of the stator winding, which in turn requires an increase in the length of the 'air gap' to maintain a given short-circuit ratio, this being a measure of the 'electrical stiffness' of a machine and its ability to operate under conditions of leading power factor.

The direct-cooled alternator for Willington 'A2' was therefore designed with an 'air gap' length of $4\frac{1}{2}$ inches compared with that of a conventional machine of $2\frac{1}{4}$ inches for the same short-circuit ratio.

A further effect of the increase in electrical loading is an increase in the internal reactance of the machine, which while somewhat adversely affecting the full-load excitation has a beneficial effect in reducing the required breaking capacity of the associated switchgear.

The construction of the machine follows standard lines, except for the special features associated with the ventilation arrangement.

Overall Machine Ventilation Arrangement

The isometric section shown in Fig. 4 illustrates the general principles of the ventilation circuit, from which it can be seen that the hot gas discharging from the active components is first cooled by passing upwards through the coolers in the slipring-end half of the machine. After this first-stage cooling the gas enters the blower from which it is conducted downwards through the coolers in the turbine-end half of the machine to extract the blower adiabatic losses. The re-cooled gas is then directed to the high-pressure end of the ventilating circuit and passes through the stator core and coils and rotor in parallel.

A separate high-pressure zone at the slipring end of the machine, communicating by pipes with the turbine end, enables both ends of the rotor to be ventilated separately.

The cool gas is admitted to the stator coils and core at the turbine end of the alternator to maintain shaft alignment with the turbine.

Stator Core

As in conventional machines, the core is flexibly mounted inside the main stator frame. The axial gas passages consist of small-diameter holes suitably disposed in the core and teeth to maintain a uniform temperature across the section. The stator core endplates have holes drilled to line up with those in the core. Before inserting the stator coils, air flow tests were carried out to ensure that there was no blockage or leakage.

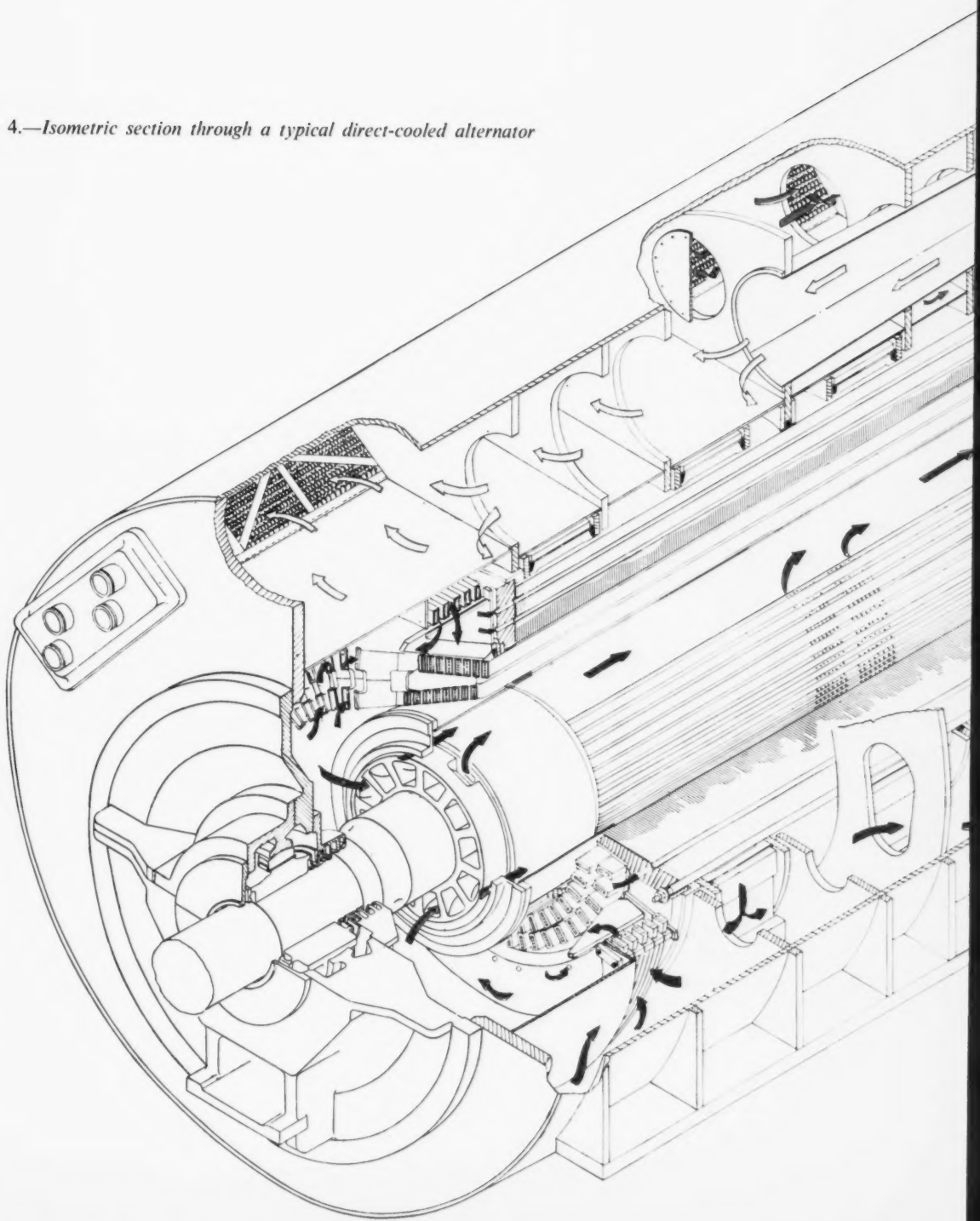
Since the two halves of the machine are at appreciably different pressures a specially designed seal is fitted between the coreplates and frame to prevent leakage from the high pressure to the low pressure side.

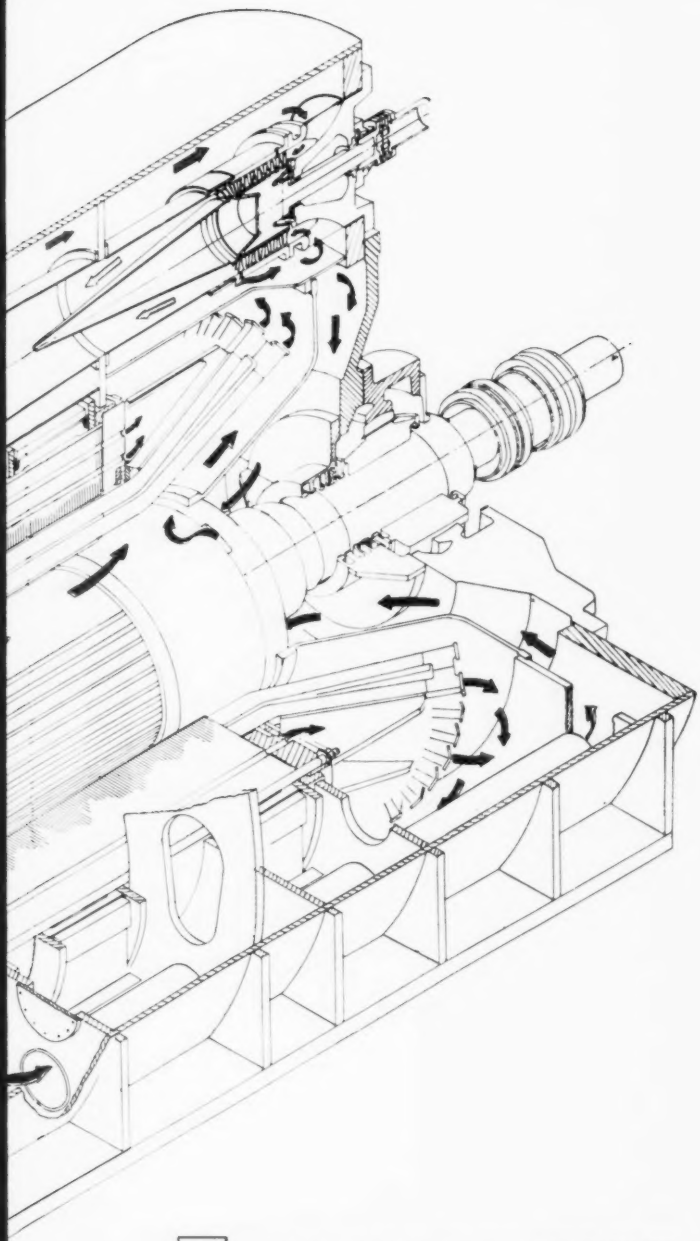
Stator Winding

This is of the standard basket type with two coil sides per slot, each carrying the phase current. A coil side consists of two conductors transposed using the Roebel method of transposition and separated by a stack of thin-walled lightly insulated phosphor bronze tubes. Additional transposition at the ends of the coils is arranged to reduce the eddy currents produced by the end-winding leakage flux, and to take into account the slight phase displacement between the two conductor groups introduced by the presence of the tubes. Special precautions were taken when forming the tubes to prevent distortion and possible blockage.

The cool gas enters and leaves the tubes in the stator coils through special shields made of insulating material which are rigidly attached to each coil evolute, the distance from the ends of the shields to the frame being adequate to maintain the required sparking and creepage lengths. The maximum copper temperature occurs at the gas exit of the coils at the slipring end of the machine.

Fig. 4.—Isometric section through a typical direct-cooled alternator





GAS DELIVERED BY BLOWER TO 2nd STAGE COOLERS

COLD GAS AFTER 2nd STAGE COOLING

HOT GAS TO 1st STAGE COOLERS

GAS INTAKE TO BLOWER AFTER 1st STAGE COOLING

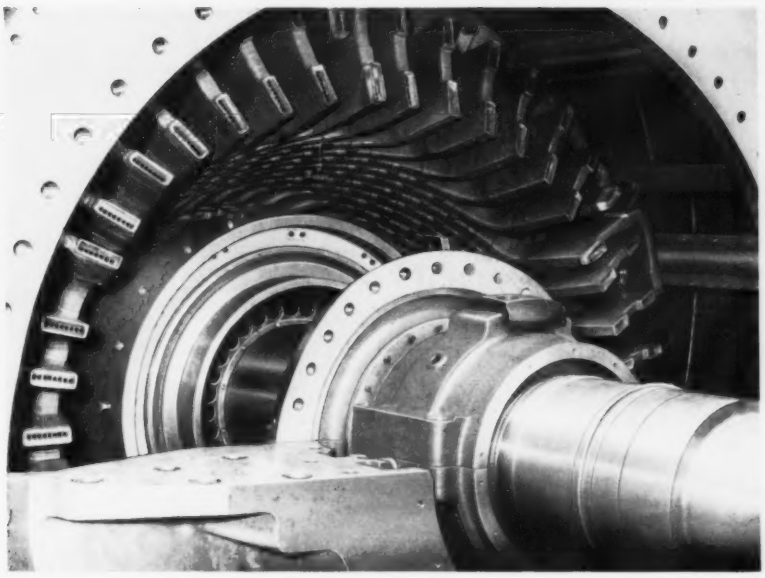


Fig. 5.—End-windings of direct-cooled stator, showing separate gas ducts

Air flow tests were carried out at several stages of manufacture of the coils, and after the winding had been completed, to ensure that there were no restrictions in the tubes.

The coils were designed for a copper temperature rise of 90°C at the point where the gas leaves them. This is the same as for conventional machines after allowance has been made for the effect on the

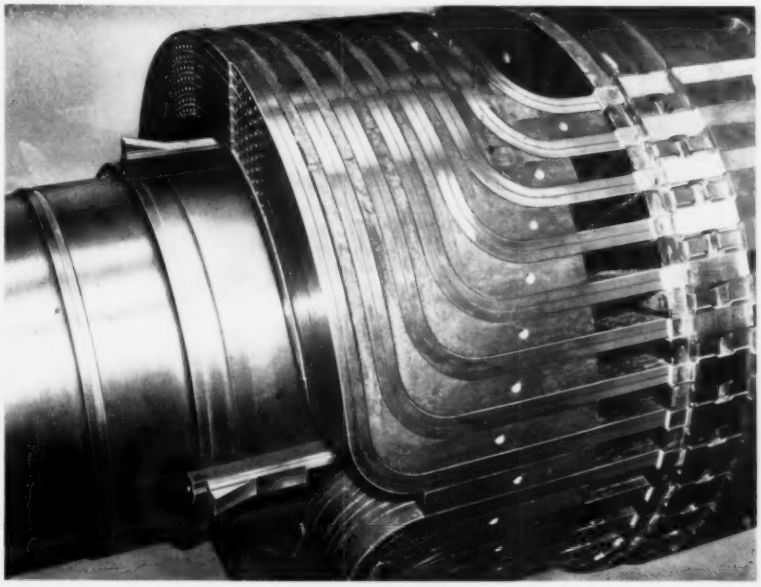


Fig. 6.—End-windings of direct-cooled rotor

standard embedded temperature detectors of the thermal drop through the insulation. Fig. 5 shows the gas ducts in the stator coils.

Because of the high currents involved the terminals themselves are of tubular construction, enabling cool gas to pass in direct contact with the copper. This ensures more efficient cooling and shows a significant saving in weight of copper compared with solid terminals. The insulation consists of bakelised paper moulded on to the copper, and the terminals are firmly supported by a gas-tight damping arrangement. Gas flow through the terminals is effected by positioning the inlet and outlet ports in high pressure and low pressure zones respectively.

Rotor Body and Shaft

The rotor forging is of a plain carbon steel with longitudinal slots machined in the body portion, in which the field windings are inserted.

Just outboard of each rotor end-winding retaining ring cover a baffle, in the form of a steel ring, is shrunk on to the shaft. These rings are in no way attached to the retaining ring covers, and fretting troubles are thereby avoided. The function of the baffles is to direct the cool gas to the rotor gas inlet ports and convey the hot gas discharge away from the end portions of the windings, as can be seen in Fig. 3.

As in conventional rotors, drilled and tapped holes are provided in the rotor body and teeth for the insertion of balance weights.

Rotor Winding

The rotor winding is formed from copper tube, which is drawn to give a predetermined degree of hardness ; there are two tubes in parallel forming one conductor. In order to raise the annealing temperature well above the maximum operating temperature likely to be experienced in service, the rotor copper contains a small percentage of silver in accordance with a practice which has been followed for many years on conventional machines. The tendency for the phenomenon of copper shortening to occur is very greatly reduced by this and other inhibiting features peculiar to the ventilating system adopted, i.e., the hot-spot temperature of the copper in the hottest coil is kept

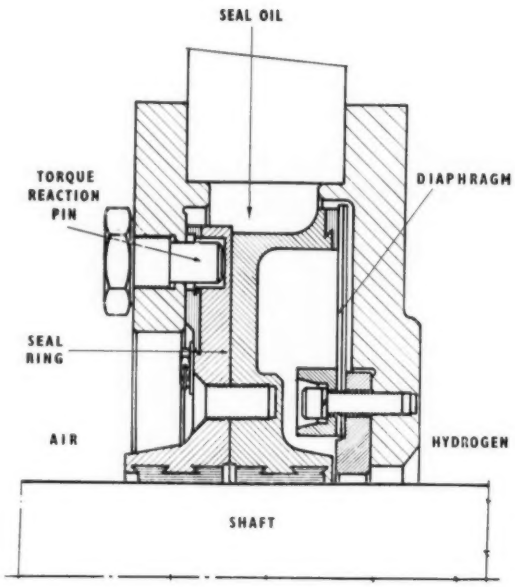


Fig. 7.—Napier balanced diaphragm seal

within predictable and acceptable limits, and the temperature distribution within the depth of the slots is far more uniform than in other forms of winding. In addition, since only a small fraction of the heat generated within the conductors flows out through the insulation and steel, the copper-to-iron temperature difference is very small.

It will be observed from Fig. 3 that the ventilation arrangement is symmetrical about the planes of symmetry of the rotor. Hydrogen enters the ends of the rotor via the annulus formed between the end turns and the shaft. After passing outwards through the spaces between the coils, where the packing blocks are removed locally, the gas enters the tubular conductors through the specially shaped side-entry ports cut in the side walls.

In all but the two inner coils in each pole the gas divides into two streams, one of which flows along the slot portion and at the rotor centre-line exhausts through radial holes drilled through the whole of the conductors in the slot depth, and lining up with holes drilled in the slot wedges. A baffle is inserted in the tubes to separate the inward flows from each end. The other stream flows around the

end turns and exhausts at the mid-region through axial holes in the tube side-walls, provision being made for separate discharge paths for each pair of tubes forming one conductor, with suitable drilled holes in the inter-coil packing blocks. After flowing through holes in the retaining ring cover the gas discharges into the 'air gap' at the cool end of the machine and into the space between the rotor and stator coil end-windings at the hot end. A small flow of gas along the 'air gap' from the cool end to the hot end is arranged to prevent the hot gas from the rotor from overheating the tips of the stator teeth.

The use of separate end-turn and slot flows enables the longest flow path to be reduced to a minimum, with a corresponding reduction in pumping losses. In the case of the first two coils nearest each pole centre, since they are much shorter, a single path is used with the gas entering the side ports at the mid-region of the end-windings and exhausting at the centre of the rotor as for the remaining coils.

The side-entry method of introducing the gas to the conductors enables the outlet ducts in the slot portion to be aligned correctly, and any relative movement of the end turns does not affect the flow through the coils. Further, since each coil in the slot depth is ventilated separately, the gas flow through each path is almost identical, with the result that, as previously mentioned, the temperature distribution within the slot depth is much more uniform than in other designs. This

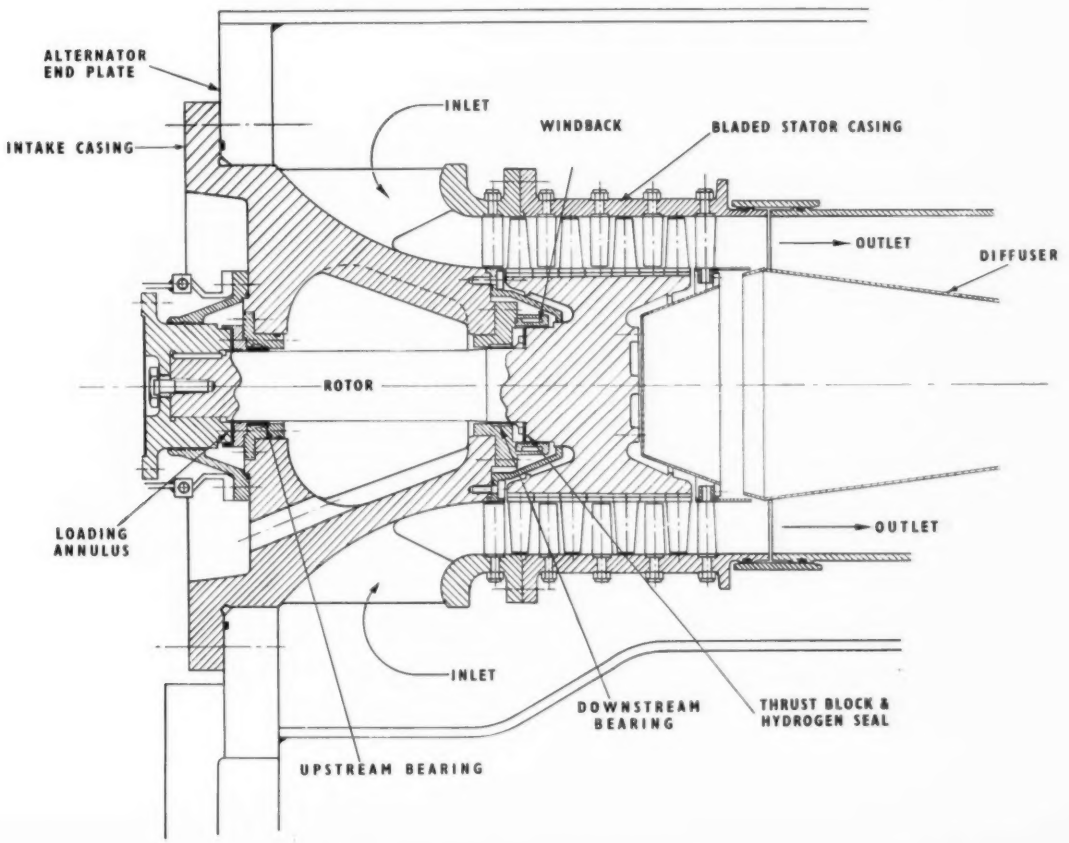


Fig. 8.—Hydrogen blower, general arrangement

Fig. 9.—Hydrogen blower, exploded view

feature, particularly, considerably reduces the risk of misalignment occurring in the region of the radial exhaust holes.

It has already been mentioned that each conductor consists of two tubes in parallel. This construction facilitates the forming of the conductors. There is also a slight reduction in the ventilation and excitation I^2R losses as compared with a conductor having a single duct, and further a complete box structure is most stable mechanically and gas leakage is avoided. The duct size is proportioned to give the minimum total power losses, as in the stator duct design.

The conductors are assembled in moulded mica troughs which fit closely in the slots, with separators of asbestos base material laid between conductor layers to avoid the use of mica, which could flake and cause blockages. A strip of micanite is moulded into the bottom of each trough as reinforcement for the corners.

Brazing of the end-turn joints was carefully controlled to ensure that any annealing of the copper was confined to small areas either side of the joints. A self-fluxing brazing alloy was used and each joint thoroughly inspected and tested ultrasonically as winding progressed.

In order to satisfy creepage distance requirements, synthetic-resin-bonded glass laminate was laid between the copper damper strip and the top conductors, the copper strip being stopped off either side of the radial exhaust holes to allow a deeper insulation layer below the wedge. The insulation at this point is, of course, drilled with holes to line up with the exhaust holes in the conductors and wedges.

Circumferential packings in the region of the end-turn exhausts are suitably drilled to provide gas passages. Fig. 6 shows the completed end-winding of a direct gas cooled rotor.

The hot-spot temperature rise of the copper was designed not to exceed 90°C, resulting in an average temperature rise of under 60°C, as measured by increase in resistance.

Tests during manufacture of the rotor included the usual high-voltage tests on the lined end-winding retaining rings, individual slot insulation troughs and wound rotor. In order to ensure that all gas passages were free from restriction, an air flow test was carried out on the completed rotor. Finally, before combined works tests with the alternator, the rotor was overspeeded to 3,600 r.p.m. for 5 minutes in the overspeed test laboratory and dynamically balanced and seasoned at normal working temperature in a special rig.

Sliprings and Brushgear

The sliprings are steel forgings shrunk on to steel hubs, insulated with mica. Because of the heavy excitation current each ring has a ' double-track ' collecting surface, spirally grooved, and the design is such as to ensure uniform current distribution. They are arranged side by side outside the outboard bearing and enclosed in a ventilated housing, the air being circulated by a centrifugal fan mounted

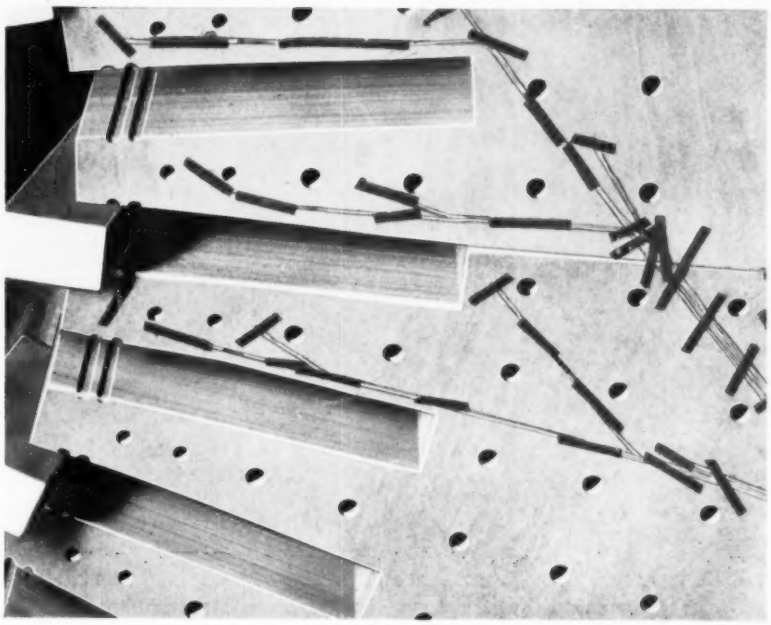


Fig. 10.
Group of thermo-couples for measuring iron temperature of stator core

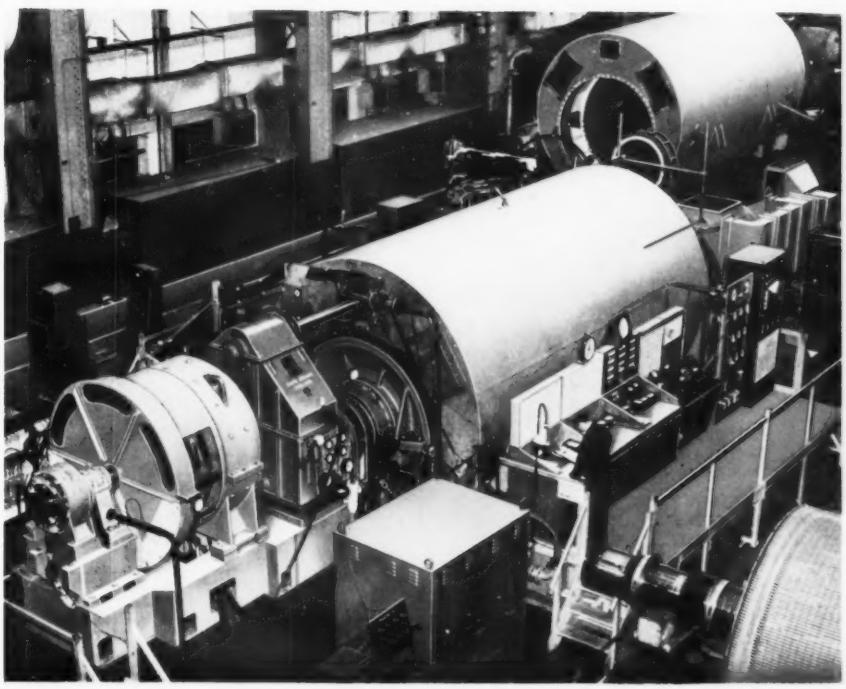


Fig. 11.—*Direct-cooled alternator on works test*

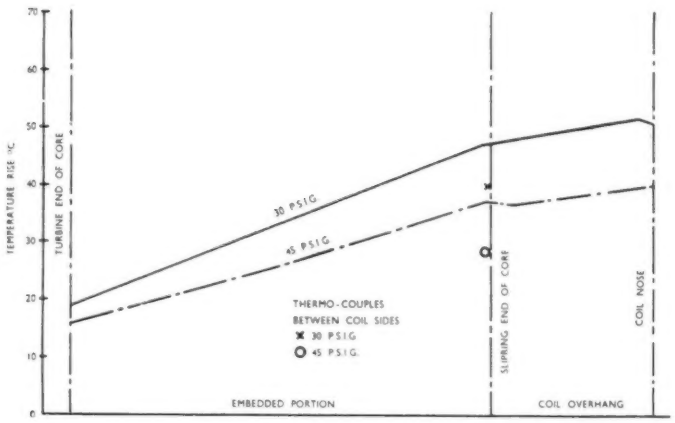


Fig. 12.—Copper temperature rise on works kVA tests of stator coils nearest bore

adjacent to the sliprings, and drawn from the station atmosphere through a filter. The rings contain radial ventilating ducts to aid the circulation of the ventilating air, and the enclosure is suitably baffled.

The leads from the windings are carried in dovetail grooves in the shaft to two radial copper-alloy studs connecting to two semi-circular copper bars located in the central bore of the forging. A second pair of radial studs on the outboard side of the bearing make connection with the sliprings. Gas-tight joints are provided at both the inboard and outboard radial studs.

Hydrogen Shaft Seals

The main alternator seals are of the ring type, developed in conjunction with D. Napier & Son Ltd and employing the principle of hydraulic balance. They are as shown diagrammatically in Fig. 7. Oil is pumped to a feed groove halfway across the sealing face, flowing both ways along the shaft through the clearance space between the rings and shaft. The maintenance of an oil feed pressure above the machine pressure ensures that oil will flow towards the hydrogen side of the seal, preventing the escape of gas from the machine.

Since the blower is of the overhung type it requires only one seal and this is of the face type. It serves also as the thrust bearing and is situated on the inboard side of the downstream bearing. A surge face is provided at the upstream bearing to which oil is supplied to ensure that the thrust collar of the blower is at all times held against the thrust and seal face of the downstream bearing. Napier wind-back oil seals are used to preclude any risk of oil entering the gas side of the blower at speed.

The oil for the seals is supplied from the normal seal-oil treating unit which provides vacuum treatment of the oil to prevent ingress of air into the alternator and to maintain the highest hydrogen purity possible.

Hydrogen Circulating Blower

The blower is of a four-stage overhung design having constant fluid inlet angle to the stator blades to reduce Mach Number effects, particularly since it has to operate surge-free in air as well as hydrogen.

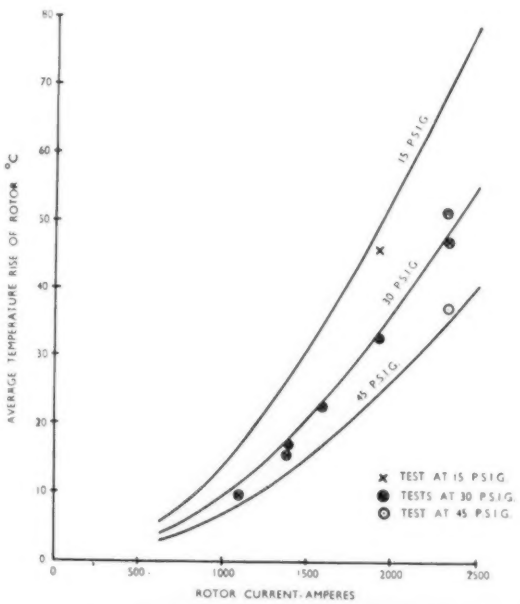


Fig. 13.—Rotor winding temperature rise on works tests

The general arrangement of the blower is shown in Fig. 8. The rigid intake casing carrying the bearings and combined thrust block and hydrogen seal is bolted to the alternator end-plate, and the bladed stator casing is supported by four spokes from the intake casing. The stator blades have adjustable stagger.

An exploded view of the blower is shown in Fig. 9.

Temperature Measurement

In order to obtain as complete a picture as possible of the temperatures existing in the machine, upwards of 250 temporary thermo-couples were built into the alternator stator and gas circuit during construction and erection, in the following positions :—

1. In the stator iron, ranging from the tips of the teeth to the back of the core at five sections along the length. Fig. 10 shows a typical core section with thermo-couples in place.
2. In the stator core end-plates, both near the surface and embedded 2 inches in the metal.
3. On the outermost strip of copper of the neutral conductors at both extremes of the embedded length, in similar positions on the conductors as they enter the overhang portion, and at the extreme ends of the overhangs at the slipring end.
4. On the phase connection rings and terminals.
5. On the stator shell.
6. Inlet and outlet cooler gas passages and at inlet to and exit from the cooling paths of the stator.

Permanent temperature detectors were embedded in the stator teeth $1\frac{1}{2}$ inches from the hot end of the core and between coil sides at the same axial position.

Works Tests

The successful outcome of the development and new manufacturing techniques evolved was established by the works tests on the machine, which were completed at the beginning of 1958. The alternator was erected with gearbox and exciter and driven by an induction motor of known efficiency. Fig. 11 shows the machine and its auxiliaries erected for works tests. In addition to the normal works tests, consisting of determining the open-circuit and short-circuit characteristics, measurement of losses, instantaneous short-circuit test and open-circuit and short-circuit heat runs, the machine was subjected to a series of heat runs on reactive kVA at varying gas pressures, to confirm the design basis, in accordance with the Company's policy in testing all prototype machines of large output and new design.

The characteristic-curve tests were carried out with normal gas cooling, since the permissible currents and voltages of direct cooled machines fall off rapidly as the gas pressure is reduced below the normal value. This is due, of course, to the greater dependence in this type of machine on the actual mass flow of the coolant. While no rating of significant value can be assigned to such machines when running in air, a series of heat runs was carried out in air to establish what air rating was possible. As expected, the limiting feature was found to be the rotor heating, and the maximum kVA proved to be 20%.

An instantaneous short-circuit test was carried out on the insistence of the Central Electricity Generating Board at 50% and 100% of the rated voltage of 13.8 kV.

Results from Works Tests

The results of the kVA heating test carried out at rated stator current and rated excitation were very close to the predicted performance. It was not possible to operate at rated voltage since the excitation would have exceeded the permitted value. The test terminal voltage of 11,000 volts chosen was such that the machine internal voltage was approximately 90% of that calculated as obtaining under the full-load terminal condition of 100 MW 13.8 kV and 0.9 p.f.

Fig. 12 shows the temperature rises obtained on the stator coil thermo-couples, temporary and permanent. It can be seen that the temperatures indicated by the thermo-couples between coil sides are approximately 7°C lower than those indicated by the thermo-couples on the copper of the coils nearest the bore. There are two reasons for this : firstly, the full stator core heating was not present, and secondly, the coils nearest the bore are invariably hotter than those remote from the bore, as the result of the difference in eddy currents.

As regards the rotor, it was only possible to measure the average temperature rise, obtained by

increase in resistance, and the results are shown in Fig. 13. The full lines indicate the predicted average temperature rise.

The short-circuit ratio obtained from the open-circuit and short-circuit characteristics was 0.78, and the synchronous impedance 135%.

Further Tests at Site

Shortly following the commissioning of the unit in October 1958, a preliminary heat run under rated conditions was carried out. The results indicated a temperature rise of 45.5°C measured by the thermo-couples between coil sides, and 50.5°C measured by the permanent thermo-couple in the stator teeth. The average temperature rise of the rotor was 50°C.

It is intended to carry out further heat runs at site on the alternator at various loads and power factors, leading and lagging, at gas pressures of 30 and 45 p.s.i.g.

Automatic Starting of Diesel-Alternator Sets at a General Post Office Exchange

By T. J. PAVITT, formerly of Switchgear Contracts Department, Stafford.

WITH the extension of the British electricity grid system, which is now being reinforced by the 'super grid', the failure of power supplies would appear to be almost a thing of the past. However, there are certain important services which must be maintained at all costs in the public interest or for security reasons, and whilst the possibility of a failure due to bulk supply disconnection is remote, that of a fault in the distribution at the load point must also be considered. Thus standby supplies must still be provided for essential purposes such as telecommunications.

The Birmingham Anchor Exchange is a new and important telecommunications centre. Its introduction was dictated by the rapid growth of telephone services and the initiation of the trunk dialling system in Britain. As failure of the power supplies to this centre could seriously affect the communications network of this country, considerable standby plant has been installed and is described in this article, with particular reference to automatic starting.

Main Supply

The main power supply to the Anchor Exchange

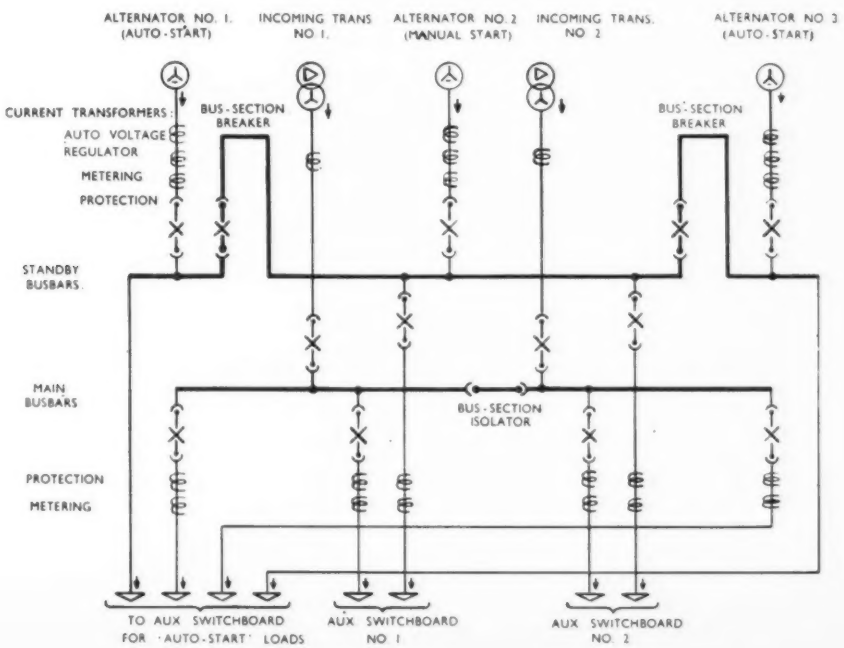


Fig. 1. Key diagram of switchgear, 415 volts 3-phase 4-wire 50 cycles

is obtained from the Electricity Board's 11 kV network via two 800 kVA 11,000/415 volt double wound air-blast-cooled transformers with closed air circuits and air-to-air heat exchangers. The supply to the cooling-fan motors etc. is obtained direct from the secondary terminals of the associated transformer. A complete spare cooling assembly is provided for each transformer.

Standby Supply

The standby supply is obtained from three 300 kVA diesel generating sets, each comprising a 400 b.h.p. Crossley engine driving a 270 kW 0·9 p.f. 415 volt 3-phase 4-wire alternator at 600 r.p.m.

In order to reduce to a minimum the interruption in the supply to certain essential equipment in the event of a mains failure, two of the three generating sets are arranged for automatic starting.

The engines have compressed-air starting motors operating at 450 p.s.i., by means of which they can attain their full speed in well under 10 seconds from initiation of the starting sequence.

Switchgear and Control Gear

The control of the 415 volt 'mains' and 'standby' supplies is by means of an 'English Electric' 12-panel 2-tier double-busbar switchboard, the 11 kV/415 volt incoming transformers being connected to one set of bars, and the standby generators to the second set, as shown schematically in Fig. 1.

This switchboard includes automatic control gear to perform the following functions :—

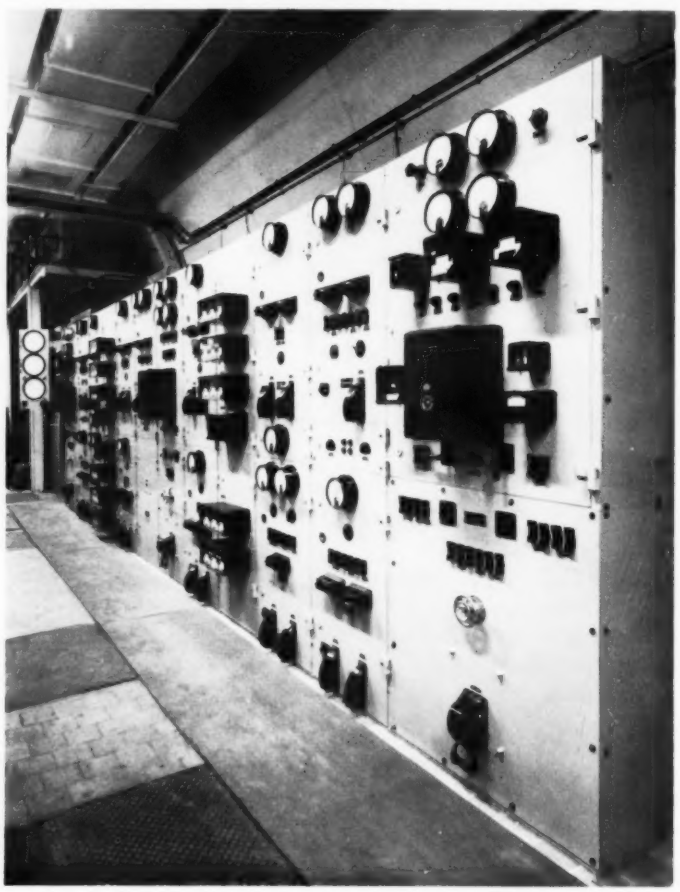
(*a*) To detect mains failure, and extend a starting signal to the automatic starting equipment associated with the engines.

(*b*) To effect transfer of the load from 'mains' to 'standby' as soon as the voltage of the alternator selected for automatic starting is within prescribed limits.

(*c*) To monitor the alternator output, and maintain a stable emergency supply.

Only a part of the total load on the 415 volt switchboard requires rapid restoration of the supply, and this partial load is well within the capacity of one generating set. Provision is therefore made for selecting either of the two automatic starting sets to start on mains failure.

Normally No. 1 Set will be selected for auto-starting duty, and No. 3 Set will be available for starting under manual control if required, or for selection for auto-starting in the event of No. 1



Photograph by courtesy of H.M. Postmaster-General

Fig. 2.—The main 415 volt switchboard

being out of commission. No. 2 Set is arranged for manual starting should the failure of the main supply persist, and secondary essential loads need to be reinstated.

The switchboard is of the totally enclosed, fully interlocked, air insulated, steel cubicle type, as shown in Fig. 2, with 'OB3' air-break circuit-breakers having a breaking capacity of 26 MVA at 415 volts. It includes three alternator control panels and two main protection panels. Mounted at the left-hand side of the switchboard is the hinged synchronising panel, which includes indicating lamps for 'lamps dark' synchronising as well as the synchroscope.

The use of air-break circuit-breakers, by the elimination of oil, minimises the fire hazard and generally simplifies maintenance, particularly as the 'OB' type of breaker is capable of complete isolation by means of 'scissor' contacts when it is withdrawn to the maintenance position, as illustrated in Fig. 3.

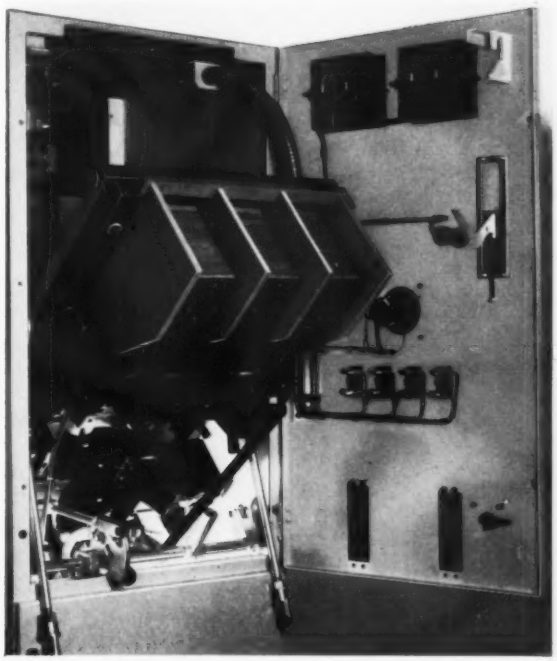


Fig. 3—An OB3 circuit-breaker in isolated maintenance position

The circuits are protected by current-transformer-operated overcurrent and reverse-power relays, mainly grouped on two separate panels shown in the centre and on the left of Fig. 2. Special test blocks are wired into the protective circuits for injection-test purposes. The alternator voltage control is by means of carbon-pile regulators, which are mounted on the alternator panels together with the associated engine alarms. The auto-starting relays are mounted behind the hinged front panel of the alternator cubicle as illustrated in Fig. 4, special attention having been paid to the accessibility of the control equipment.

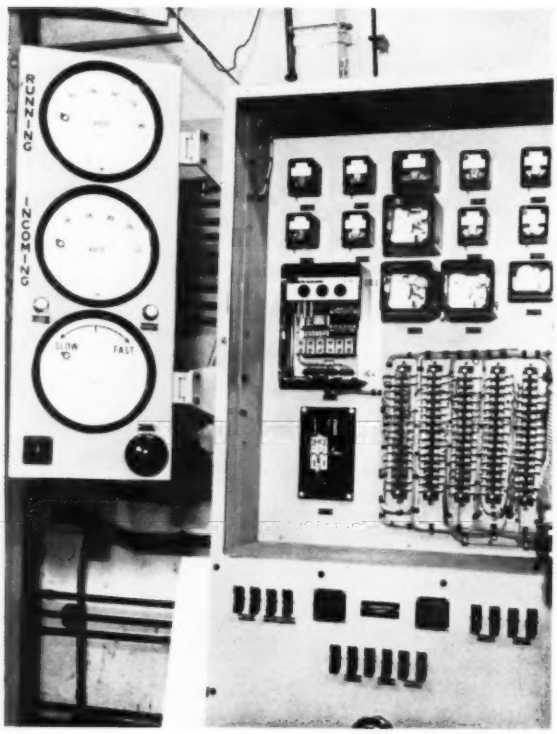
Standby Load Distribution

The distribution of the load from the main 415 volt switchboard to the circuits which require automatic restoration of the supply is via an auxiliary switch-fuse board. There is a 'standby' feeder to this auxiliary board from each automatically started set, and there are two corresponding feeders to it from the 'mains' busbars on the main 415 volt switchboard.

Electrical interlocking is provided to ensure that both circuit-breakers controlling the mains feeders to the auxiliary switchboard are tripped out before the solenoid-operated alternator circuit-breaker associated with the selected auto-starting set can be closed. Castell key interlocking between the two standby feeder isolators on the auxiliary switchboard prevents paralleling of the two auto-starting sets through the auxiliary switchboard, and auxiliary contacts on these isolators prevent the 'set selected' indicating lamp on the control panel from lighting unless the correct isolator is closed.

Normal Load Distribution

The distribution to the remainder of the load on the premises from the main 415 volt switchboard is made via two other auxiliary switch-fuse boards, each having a duplicate feed, one from the standby busbars and one from the mains busbars. The circuit-breakers controlling these feeders are interlocked by Castell keys to prevent interconnection of the mains and standby busbars through the auxiliary switchboards.



Photograph by courtesy of H.M. Postmaster-General.

Fig. 4.—Auto-starting control and relay panel

Automatic Starting

The automatic starting of the selected standby diesel-alternator set takes place on a comparatively small reduction in the system voltage. The exacting limits specified by the General Post Office necessitated a 3-phase electronic detecting relay with adjustment over the range of 80%-95% of the nominal voltage, and having a very low pick-up/drop-off differential. This relay operates to initiate the starting sequence if the mains voltage falls below the pre-set value, or on complete mains failure, on any phase or between any two lines. A valve failure in the relay itself will also initiate starting, but as its components are all of high stability, and its circuits run well below their full rating, the relay is as reliable as any sensitive moving-coil type. Special resistors are provided in the grid circuits to prevent parasitic oscillation of the valves.

Under normal conditions both 'mains' circuit-breakers controlling the supply to the auxiliary switchboard are closed, and the associated 'standby' circuit-breakers are open. One diesel-alternator set has been selected for auto-starting, the selection being made by two control switches, one on each alternator control panel, which are interlocked to prevent both being closed at the same time.

The control switch will have prepared the circuit of the selected alternator for the auto-starting condition; the appropriate 'standby' switch on the auxiliary switchboard will be closed, the bus-section breaker on the standby bar of the main switchboard open, and the automatic voltage regulator changeover switch set to the 'auto' position.

The above conditions being satisfied, and provided the engine-starting compressed air system is under pressure, the 'set selected' lamp lights, indicating that all circuits are correct for auto-starting, and that on mains failure the chosen alternator will run-up and take over the load.

The detecting relay previously described, if the mains voltage falls below its setting value, operates the master control relay, which extinguishes the 'mains on' indicating lamps and prepares the circuits for actuation of the engine auto-starting equipment. It also prepares the trip circuit for the mains circuit-breaker, which is tripped when the alternator is ready to take over the load.

It is essential that both mains feeds to the auxiliary switchboard controlling the 'auto-start' loads shall be disconnected before the selected alternator is connected, to avoid paralleling the alternator with the mains via the busbars of the auxiliary switchboard, and this is ensured by electrical inter-tripping between the control circuit of the selected alternator and both mains circuit-breakers via a master control relay.

The automatic starting equipment for the engine discriminates between a complete failure of the mains and low mains-voltage. In the former event the engine is started immediately, whereas in the case of low mains-voltage a delay of approximately

2 seconds is introduced to avoid unnecessary starts due to switching surges etc.

The engine starting sequence having been completed, and the engine having ' fired ' and run up to speed, the alternator voltage builds-up under control of the automatic voltage regulator. When the voltage comes within the normal operating range the voltage relay operates and, by means of timing relays, allows the alternator voltage to settle down before the load is applied, and withholds the operation of the alarm circuits. Having completed the delay, the relay prepares the circuit of the closing contactor for the ' standby ' circuit-breaker, opens the trip-coil circuit of this breaker, and trips the two incoming mains circuit-breakers. The standby breaker then closes, allowing the alternator to take the load.

The alarm timing relay, having now completed its delay period, reinstates the alarm circuits. Should the alternator not achieve the required condition for taking load, its circuit-breaker is prevented from closing and the appropriate alarm circuit is energised. An engine failure is detected by a separate monitoring circuit, which gives an initial warning, and shuts down the set if the fault persists.

Provision is made for the parallel running of all three diesel-alternator sets if required. Synchronising is under manual control, but parallel running with the supply authority's mains is prevented by the duplicate busbar arrangement and the interlocking features already described.

The lubricating oil systems of the two auto-starting engines are intermittently primed by a combined pump and gravity system while the engines are at rest.

Mains Restoration

Restoration of the mains supply causes the mains-failure detecting relay to pick-up and operate the master control relay, which lights the ' mains on ' indicating lamp. The standby circuit--breaker is then tripped manually by push-button, and the mains breaker is reclosed by hand. Electrical interlocks prevent the reclosure of the standby breaker before the mains breaker is closed.

On closing the mains circuit-breaker, the circuit of the closing contactor of the standby circuit-breaker is opened. This ensures that the complete mains-failure sequence is carried out before the standby breaker can be reclosed.

Control and Tripping Supplies

Two 50 volt ' Nife ' nickel-cadmium alkaline batteries with control and charging equipment have been provided, to maintain the continuous load required for indication under mains-failure conditions, to supply the power for the engine control and alarm equipment, and to perform the switch closing and tripping operations. Each battery consists of a bank of 38 cells having a capacity of 25 ampere-hours at the 10-hour rate of discharge.

The control equipment is so arranged that under normal conditions the continuous loads are supplied from the rectifier contained in the control and charging cabinet. The equipment also has means for selecting either of the two batteries for duty, the selected battery floating across the rectifier output on continuous trickle charge. Thus the battery takes the load instantaneously and automatically in the event of a mains failure. The battery not selected can be left on open circuit, or given a quick-rate boost charge.

The output from the battery selected is monitored by means of a ' Sunvic ' tube relay, which incorporates a thermal time-delay unit. This relay operates an alarm in the event of a reduction in voltage due to rapid discharge of the battery. The time delay prevents an alarm being given when the battery is called upon to supply heavy load surges of short duration for auto-starting an engine.

Test Facilities

Mains failure can be simulated by means of a push-button which carries through the starting sequence already described.

Testing of the engine control circuit and alarms can be carried out by means of a second push-button, without causing a changeover of the load.

Scope for Automatic Standby Plant

The type of equipment described in this article is invaluable in important consumer installations where standby power plant is necessary in order to avoid the possibly serious consequences of power failure, and it is significant that, even with the high degree of reliability of the British grid supply system, nuclear power stations depend ultimately on this form of standby plant for their vital control supplies and safe operation.

Acknowledgment

The author is grateful to the Post Office Engineering Department for co-operation in the preparation of this article, and for permission to publish it.

Electric Drives for Excavators

By P. W. R. GATLIFF, B.Sc., A.M.I.E.E., Chief Machine Control Engineer, Stafford.

OPENCAST COAL MINING SITES, quarries, and large-scale civil engineering projects have provided a demand in recent years for large capacity excavating equipment, and it has long been realised that electric drives, using direct-current motors on the Ward-Leonard principle, provide an excellent way of driving the various motions of an excavator, particularly on the larger sizes of machine.

The characteristics of the motor drives can be designed so that inherent torque limitation prevents overstressing of the machinery components. The maximum power can be limited within the capacities of the prime mover or supply line, while at the same time allowing heavy stall and acceleration torques. By eliminating some of the gears and clutches required in a mechanical drive, the electric drive allows a more flexible and simple machinery arrangement and reduces maintenance and ' down ' times.

The 150-RB Excavator

' English Electric ' generators, motors and control equipment have recently been installed in a series of excavators manufactured by Ruston-Bucyrus Limited (Lincoln) of the type known as the 150-RB.

This is a machine as shown in Fig. 2, mounted on caterpillar tracks and weighing about 200 tons. It has a bucket capacity of 6 cubic yards, and is designed so that it can operate either as a ' shovel ' or, by changing the ' front end ', as a ' dragline '. The two arrangements are illustrated in outline in Fig. 1.

Compactness of components together with accessibility for maintenance are prime design requirements, and as will be appreciated from Fig. 3, a good deal of machinery is fitted into the cab space, which is 18 feet wide by 27 feet long.

On the shovel excavator the bucket is attached to a handle which is a single large-diameter tube of heavy section and can slide forwards and backwards and pivot in the main boom. The machine is used for digging from ground level upwards to a maximum height of 36 feet, but it can also dig down to 9 feet 6 inches below ground level. The maximum cutting radius is nearly 49 feet. There are four drive motions :—

1. Hoisting and lowering the bucket.
2. Pushing the bucket out and retracting it. This is known as the ' crowd ' motion.
3. Rotating the upper works and boom structure on the circular track of the truck frame, known as the ' swing ' motion.

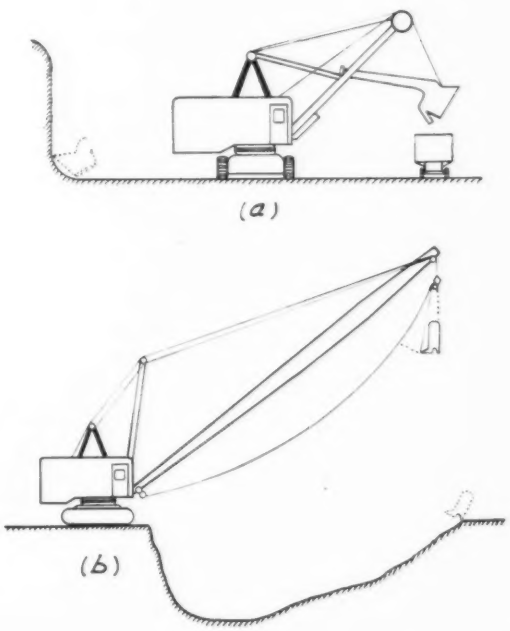
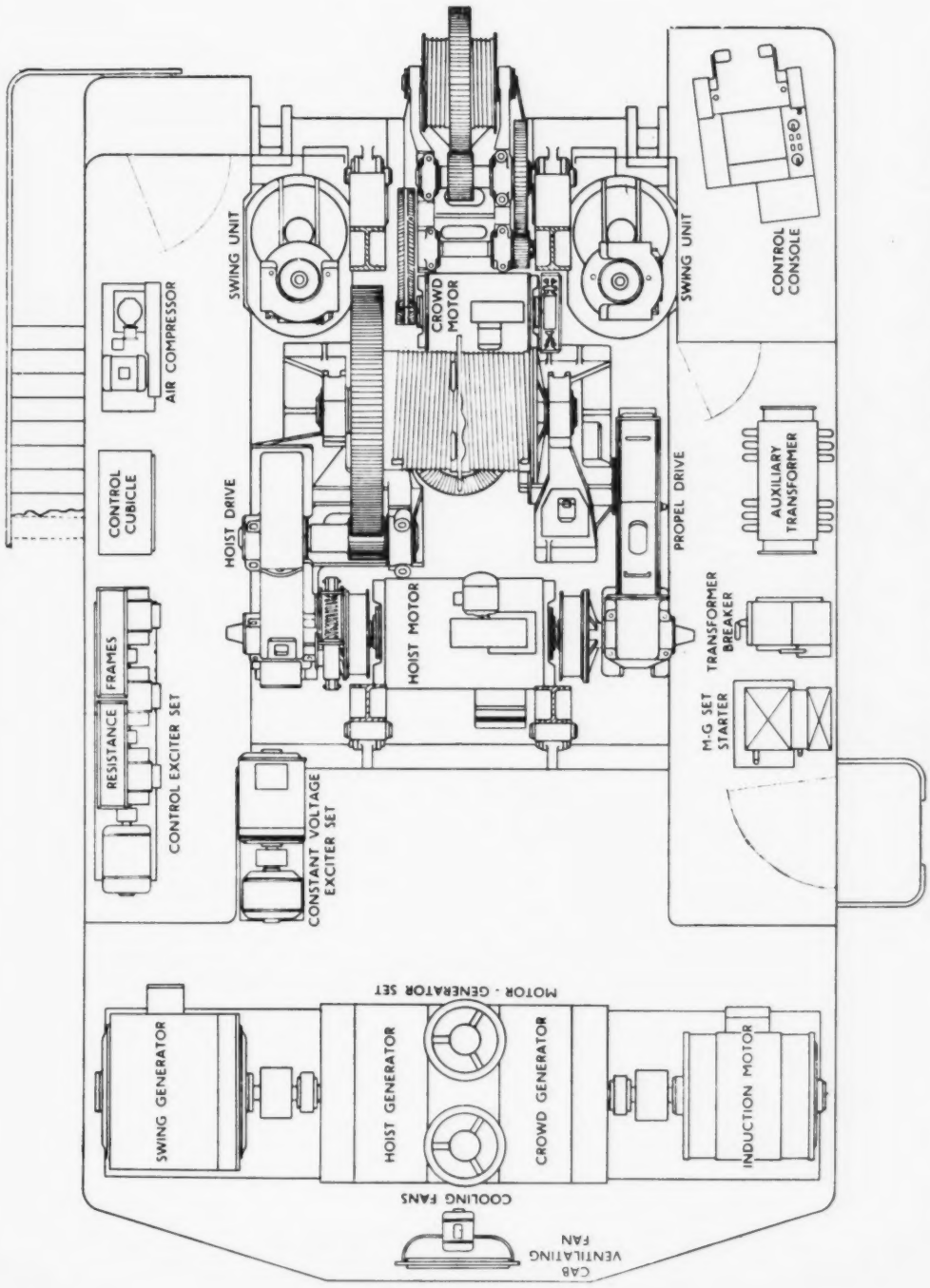


Fig. 1.—Alternative arrangements of excavator as (a) shovel and (b) dragline

Fig. 2.—A Ruston-Bucyrus 150-RB excavator, with electric drives by The English Electric Company, operating in a limestone quarry of Imperial Chemical Industries Limited



Reproduced by courtesy of Ruston-Bucyrus Limited, Lincoln.

Fig. 3.—Plan view of main machinery

The first a.c. multiple-unit train for the British Transport Commission's moder
It is one of 112 *four-car sets for the London-Tilbury-Southend line and is being*
are operating commercial services and are the first of this type to do so

Each set comprises a battery driving trailer, motor coach, plain trailer, and drivi
steel tank mercury arc rectifiers, a tap-changing transformer, tapping and sm
6·25 *kV operation are incorporated*

The English Electric Company supplied 50*-cycle train equipments for the Lancas*
in Britain, and are still running successfully. Much of the experience gained f

moderne, commissioned in November, 1958, with 'English Electric' traction equipment. being for training drivers. Subsequent sets with 'English Electric' traction equipment

d driving motor coach carries four traction motors, two pairs of air cooled single-anode nd smo, and a.c. and d.c. control gear. Automatic connections for either 25 kV or

Lancas-Heysham experimental line in 1952. They were the first of this type to operate ained reflected in the present equipments

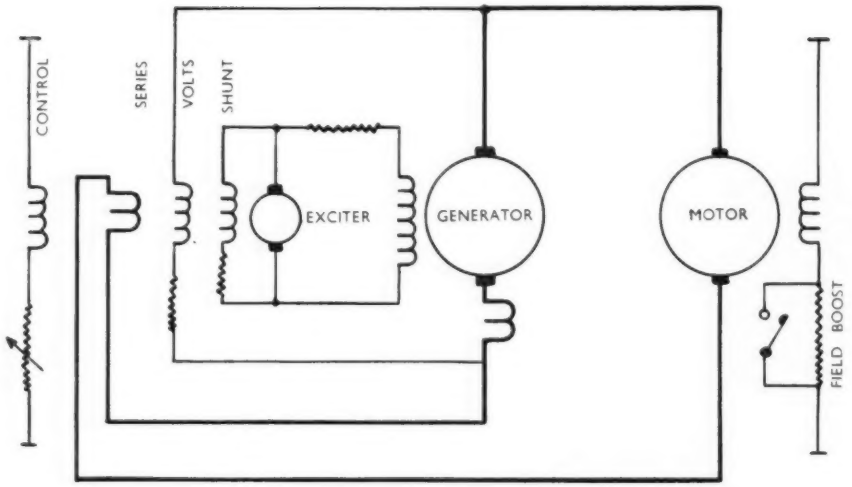


Fig. 4. — Main electrical circuit for the drive of one motion

4. Moving the excavator by driving the ' crawler ' tracks. This is known as ' propelling '.

The motions of the dragline excavator are somewhat different because the bucket is free from the structure of the machine, being controlled by the hoist ropes and the dragline ropes.

In a typical digging cycle for a shovel excavator, the machine is propelled up to the working face until the bucket is within easy reach. The brakes are applied to hold the machine firmly on the ground. The bucket is brought against the face (crowd out) and moved upwards (hoist) until it is full. The upper works are then turned (swing) to bring the bucket over the tipping area or the lorry which will carry the material away. A pneumatic device opens the bucket and allows the contents to discharge. The revolving superstructure is swung back to the face and the digging cycle recommences.

During digging the operator has to control the hoist, crowd and swing motions simultaneously. A hand lever on one side controls ' hoist ', a hand lever on the other side controls ' crowd ' and a pair of foot pedals control the ' swing '.

A similar cycle is carried out for a dragline excavator. Draglines generally dig below the level of the tracks, while shovels work at the same level or above, as indicated in Fig. 1. The dragline bucket is suspended from the end of the boom, and by a combination of lowering and paying out of the drag rope the bucket is rested on the ground. The bucket is filled by pulling on the drag rope. The revolving superstructure is then swung until the bucket is over the tip or lorry, and the material

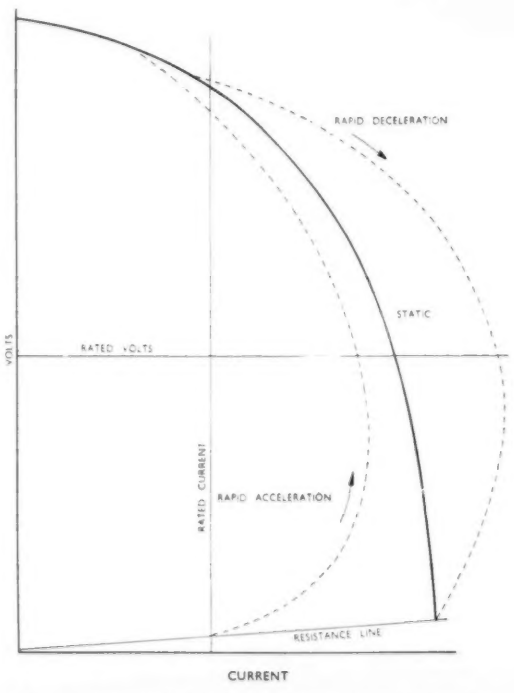


Fig. 5.—Typical generator voltage/current characteristic

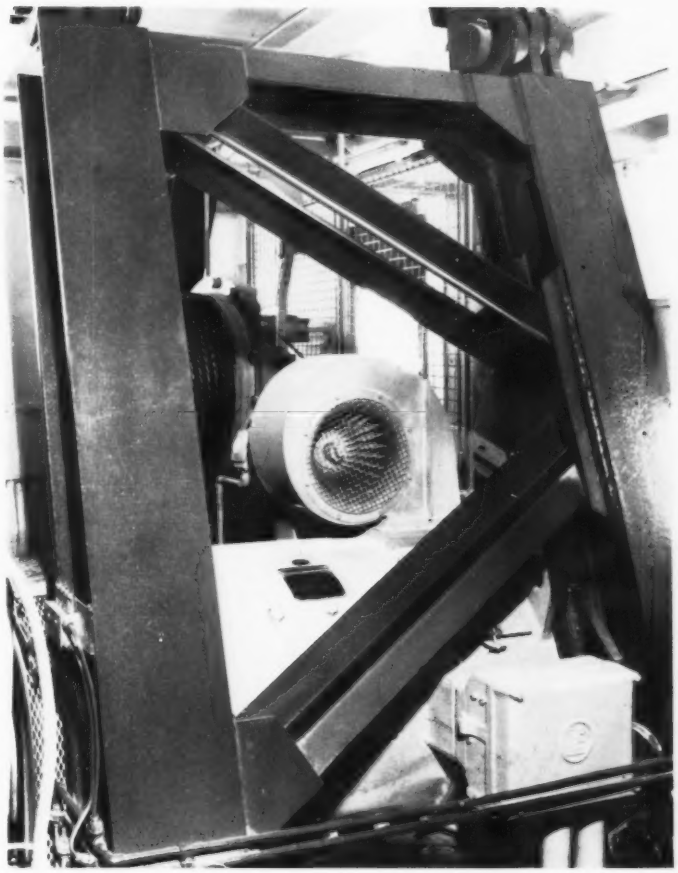


Fig. 6.—The 187½ h.p. hoist motor

is released by paying out the drag rope, which causes the bucket to tilt and empty.

Electrical Equipment

An operator and his machine will be judged by the amount of material that they can move in a shift. Operators become highly skilled in controlling all three drives at once with a minimum of lost motion, i.e. with no overshoot, yet at high speed for as long as possible. The electrical equipment must give quick response to the movements of the controllers to achieve a high machine output.

The electrical control works on the principle of the 3-field-exciter Ward-Leonard scheme, and quick response is achieved by the use of rapid-response exciters. The motor ratings (nominal) are :—

For a shovel excavator :
Hoist : 187½ h.p. 230 volts
Crowd : 44 h.p. 230 volts
Swing : 2×35 h.p. 115 volts (2 motors in series)
M.G. set drive motor : 300 h.p. 3·3 kV

For a dragline excavator :
Hoist : 187½ h.p. 230 volts
Drag : 187½ h.p. 230 volts
Swing : 2×35 h.p. 115 volts (2 motors in series)
M.G. set drive motor : 300 h.p. 3·3 kV

As propelling is not required during the digging cycle, it is arranged that the hoist motor can be declutched from the hoist drum and clutched to the propelling gear when it is desired to move the excavator. Steering is effected by declutching one crawler track and driving the other. The speed of travel is of course very slow, about 1 m.p.h. being sufficient.

Power for the excavator is provided from the electricity supply through a trailing cable, usually at 3·3 kV. The cable plugs into the truck frame between the caterpillar tracks, and the power is transferred through sliprings and heavy collector shoes to the revolving structure. Three d.c. generators supply the hoist, crowd or drag, and swing motors individually, and are driven by a squirrel-cage induction motor which is auto-transformer started. To facilitate the changeover from shovel to dragline the generator set has been designed suitable for either duty, a dual-purpose generator being incorporated. The hoist motor of the shovel becomes the drag motor of the dragline, and an additional motor is introduced for the hoist motion of the dragline. The modifications to the mechanical equipment are of

course more complex, and a changeover of this kind would not be made frequently.

Control Scheme

The electrical circuit for the drive of one motion is shown in Fig. 4. The main generator has a main excitation winding, fed from the exciter, and a series winding which is connected to oppose the main winding. The exciter has a control winding and a shunt winding which are opposed by a series winding carrying main circuit current and a generator voltage winding.

By suitably proportioning these field windings it is possible to obtain varying values of the overall voltage/current characteristic of the generator. A typical example is shown in Fig. 5 and illustrates that the stall current is twice the rated current, and the light-load volts 2·1 times the rated volts. This type of characteristic, with a separately excited motor, gives high accelerating torques from rest, and high light-load speeds, while limiting the maximum power to about 2·5 times rated power. In order to utilise a given motor frame size to its maximum capacity the motor fields are boosted during hoisting, crowding and swinging, so that more torque becomes available for a given armature current.

The characteristic shown in Fig. 5 is the static or steady-state curve. In practice conditions are never steady and the motor torques actually obtained during acceleration and stalling will differ from the static values, depending on the rapidity of response of the system. Some indication of the variation expected is shown by the dotted lines. During acceleration the time delay in the generator field reduces the current available below the steady-state value, but during rapid stalling of the motor the currents are greater for the same reason. The object of adding exciter control to apply forcing volts to the generator field is to reduce the excursions from the static voltage/current characteristic during transient conditions.

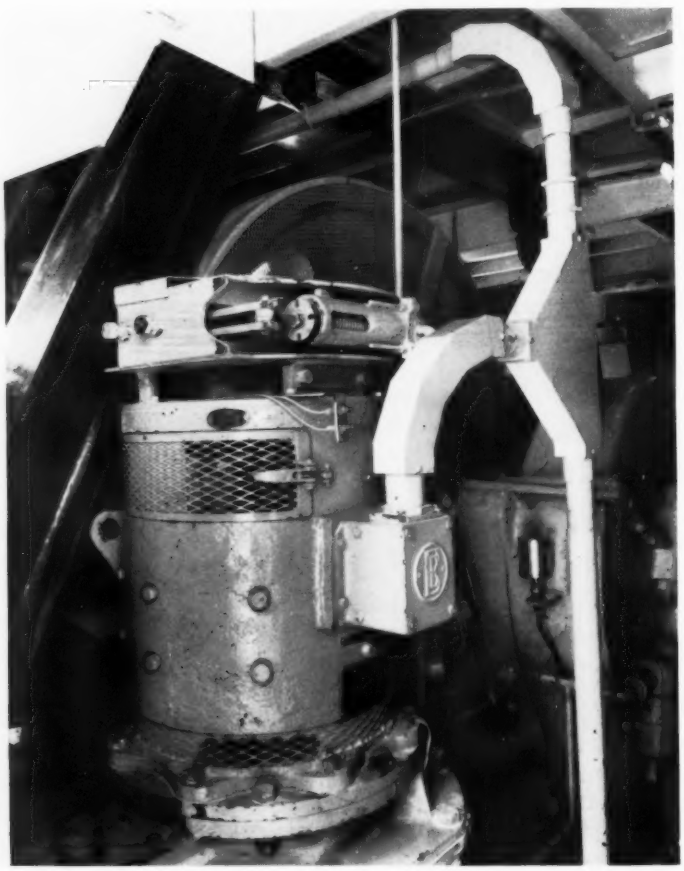


Fig. 7.—One of the two 35 h.p. swing motors

The use of exciters incidentally eliminates generator field contactors, since the master controller contacts can switch directly in the exciter control field.

Main Motors and Auxiliaries

The main d.c. drive motors (Figs. 6 and 7) are of the mill type, designed for heavy duty and forced ventilated. The generator set (Fig. 8) is built on a heavy deep-section bedplate to provide

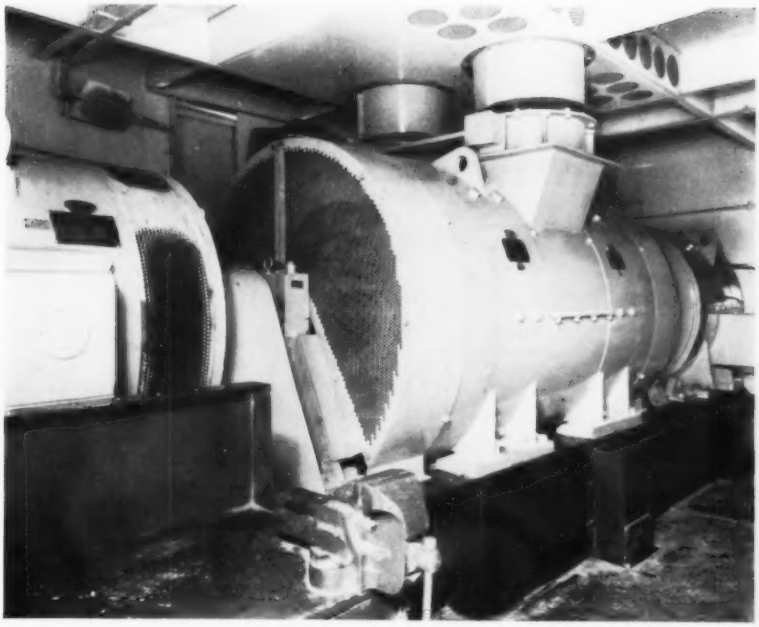


Fig. 8.—The 300 h.p. motor-generator set

a firm foundation, and assists in counterbalancing the superstructure.

The auxiliary drives comprise the exciter set, the constant-voltage d.c. exciter set for motor fields, the air compressor for brakes and clutches, and machine ventilating fans. A 440 volts a.c. supply is available for these from an auxiliary transformer.

Conclusion

These excavators have now been in service for over two years in Great Britain, and the equipment has proved itself in the excellent performance achieved.

Electrical Controls in the Steel Industry

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PART I

THE EVER INCREASING demand for the products of the Steel Industry presents the greatest challenge to the electrical engineer concerned with the control of the vast range of plant, making, shaping and finishing steel.

The considerable increase in the output of the industry since the war (see Fig. 1) has been accompanied by improvements in quality, range of product and operating efficiency. This, to a large extent, is due to the great advances in control techniques provided by the electrical engineer. New techniques, particularly in the field of automation, are being continuously evolved and will show an even greater benefit in the future.

Among the many ways in which the specialised electrical controls designed for the steel industry bring benefits are :—

(*a*) They allow higher speeds of processing, so increasing directly the potential output without a commensurate increase in capital outlay.

(*b*) They allow production in larger units, e.g. coils of strip weighing 15 to 20 tons, to give greater continuity of production with a proportionate reduction in the non-productive handling time.

(*c*) By automatic detection and control of the factors affecting the quality of the product a consistent high standard is obtained which could not be achieved by manual control. Not only is the percentage of reject material reduced, but the user is provided with a product of a quality previously unattainable.

(*d*) There is a reduction in the man-power requirements per ton of product, permitting increased production without an increase in the labour force.

(*e*) There is an improvement in working conditions for that labour force by the siting of operators' controls remote from areas of heat and foul atmosphere, and a reduction in the danger of injury.

(*f*) By greater efficiency in the use of electrical power and gas supplies the cost of these per ton of product is reduced.

The steel industry is unique in that a single works may produce several million tons annually and this may follow a single production stream for a large part of its progress through the works. There is therefore almost unlimited scope for the introduction of improved control equipment offering an increased throughput at a point in that stream. For example the saving of a fraction of a second on the pass time or the interval between passes for a primary rolling mill can increase the output of that mill by thousands of tons annually.

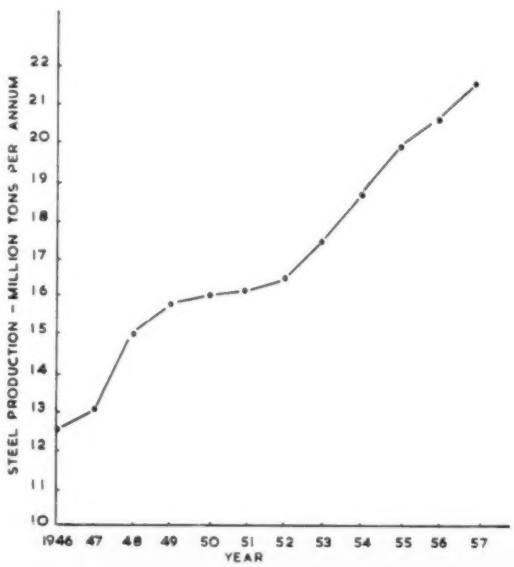
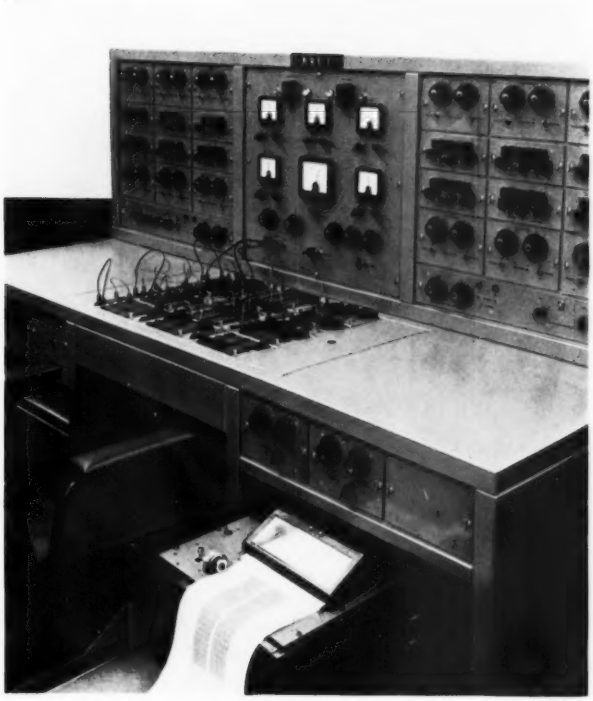


Fig. 1.—Rise of British steel production



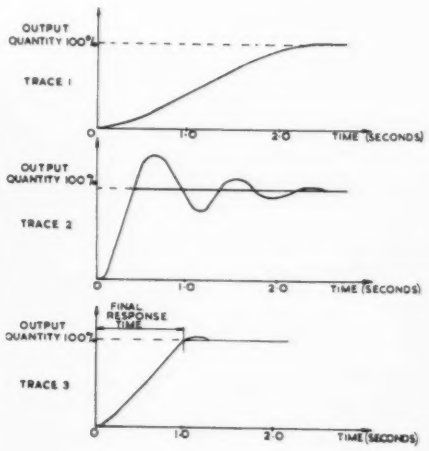


Fig. 2.—Analogue computer used in the design of rolling mill schemes, and traces obtained for three possible designs showing the different response characteristics

However, the corollary of this is that a few minutes shutdown during the working day due to the failure of an item of control equipment can cost thousands of pounds in lost production. Reliability is therefore of paramount importance, and the possibility of failure of a new item of control equipment during a production campaign, which might extend for months without an opportunity for maintenance, must be carefully balanced against the benefits that item offers.

Simple forms of control have been used from the earliest days of electrical drives in steelworks. It is the last ten years however that have seen the introduction of the more advanced automatic controls.

While the term 'automatic control' has been used in the past to cover simple remote on-off switching of circuits, or automatically sequenced operation of on-off controls, in this article it refers to the continuous servo or closed loop system of control which is self adjusting and provides the main basis of improvement in performance of steelworks plant.

The introduction of this type of control has only been possible, firstly by the development of components capable of detecting, amplifying and applying the forces needed to effect the controls, and secondly by the evolution and application of mathematical techniques virtually unknown to the steel industry ten years ago but which are essential to the satisfactory design of the more complex servo system. Among the components used in the automatic controls are load cells, magslips, photocells, electronic amplifiers, magnetic amplifiers, and high-gain multi-stage control exciters, which in their practical form are of fairly recent introduction.

The mathematical analysis of servo control systems has been developed into a tool which enables the performance of the most complex system to be accurately predicted during the design stage for all operational conditions, and furthermore it enables the control system to be designed to

give the optimum steady-state and transient performance.

This analysis has been taken a stage further in that analogue computers are now available which use simulating circuits linked up to represent the complete servo system.

The simulating circuits or analogues are electronic amplifiers which may be interconnected and modified by networks to correspond to the performance equations of the servo system under consideration.

External signals provide inputs which apply either the normal or disturbance conditions which can be expected, and the results of these can be recorded either permanently by pen recorder or transiently by cathode ray oscilloscope. These results can then be translated into the effect of various operational conditions on the full-scale system.

Fig. 2 shows an analogue computer which is used to assist the speedy design of servo control systems on steelworks drives. The inset shows traces obtained for the response to a step input of reference with three possible system designs. Trace 1 shows an overdamped system which would give a sluggish performance. Trace 2 an underdamped system giving an oscillatory response, while Trace 3 gives a good compromise.

In addition to saving considerable design engineering time and enabling more alternative systems to be investigated, the computer avoids many of the approximations inevitable in mathematical analysis. This is particularly so where there are non-linearities, such as the saturation of machine fields or the dead bands or backlash in gearboxes and couplings driving speed-measuring exciters, which may be simulated on the computer. The net result is a more accurate prediction of site performance, which enables the best system to be chosen to suit the particular requirements of that application.

IRON AND STEEL MAKING

While a great variety of electrical drives are used in the iron and steel making sections of a steelworks these are mainly for the bulk handling of materials, e.g. conveyors, transfer cars, blast furnace skip hoists, furnace chargers etc. These drives are ancillary to the main process, which is metallurgical, and the on-off type of control is normally adequate. In this, considerable complexity can arise in the automatic sequencing of operations such as scale car, skip hoist and bell movements on a blast furnace, but control is effected by relay operation. Details of this less specialised type of control are omitted from this article to enable greater emphasis to be placed on the rolling and finishing sections.

ROLLING MILLS AND FINISHING LINES

While the arrangements of rolling mills and associated finishing plant vary considerably with individual works and the class of product in which they specialise, Fig. 3 shows the general production flow through the various stages of rolling and finishing. As no single works would produce every class of product, then no works would have all the equipment shown on the diagram. The diverging routes taken by the different end products are typical only and many variations of these exist.

Steel always arrives in the rolling shops as a cast ingot and is first rolled in a primary mill which may produce slabs or blooms. From there it may pass through various hot continuous or reversing mills and possibly cold rolling mills until it reaches its finished state as plate, sheet, sections or one of the many other products.

Each particular type of mill has its own characteristics and may require control of varying form with emphasis on speed of response, accuracy of speed control, control of tension or any other variable which may affect the process involved. In the subsequent sections of this article the controls for the main types of mill are considered in detail.

HOT REVERSING MILLS

Every rolled product of the steel industry passes through one or more hot reversing mills. This classification refers to the characteristics of the mill drive rather than the design of the mill or true nature of the product.

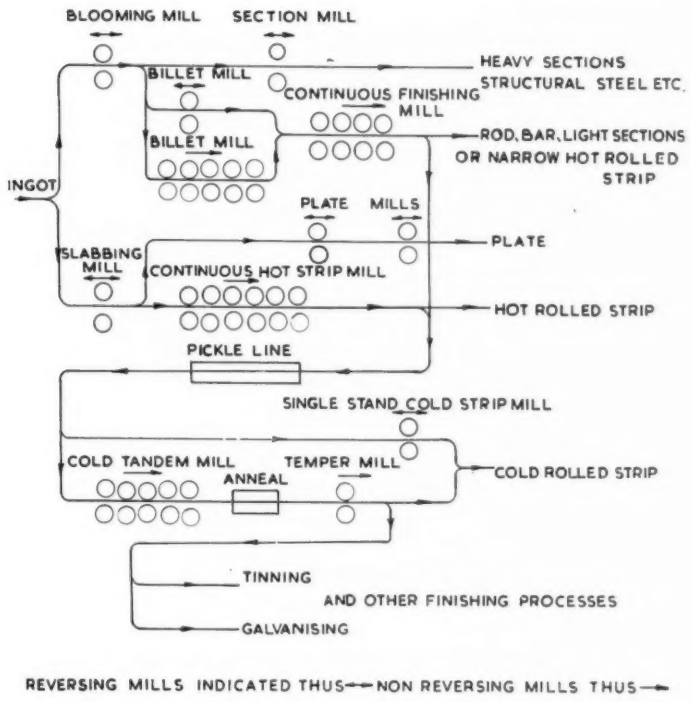


Fig. 3.—Basic flow diagram for the various products of the steel industry

Where the cross sectional area of the metal is large and its length relatively short it is convenient to pass it backwards and forwards through the same mill a number of times. For this type of rolling the temperature of the metal must be about 800°C to 1200°C.

As the piece being rolled cools rapidly at this temperature the time to complete a rolling programme is limited, so giving the need for a drive capable of :—

(*a*) Reversing frequently and in a short time to minimise the time between passes.

(*b*) Providing the very heavy torque needed to give the maximum reduction per pass.

(*c*) The greatest reliability, as in most cases a single hot reversing mill carries the whole output of an integrated steelworks so that any extended shutdown of the mill due to failure of the drive can cause a stoppage in the production of the whole works.

Hot reversing mills fall into the following categories.

1. Primary mills which receive an ingot in the form in which it was cast in the steel making shops and suitably reduce its proportions for further rolling. Primary mills may be :
   (*a*) Blooming mills producing blooms usually of near square section which are later rerolled into structural or merchant sections, bars, rods, wire or seamless tube, or
   (*b*) Slabbing mills producing wider slabs suitable for rerolling into plates, sheets or thin strip.
2. Plate mills which reduce the reheated slab to the final dimensions required for such uses as ships' plates etc.
3. Section mills which transform the bloom into the various sections of structural steel, railway track etc.
4. Roughing stands for strip mills which further reduce the thickness of the reheated slab before it is passed on to the continuous finishing stands.

The control requirements of all these mills are generally similar and are therefore considered here in fuller detail only in the case of a typical slabbing mill.

On the larger hot reversing mills it is normal to use two motors, one directly coupled to each roll, so avoiding the need for gearing. In the following example each motor has an r.m.s. rating of 6000 h.p. over a speed range of 50 to 80 r.p.m. with a working peak torque of 2½ times and a cut-out peak torque of 3 times the r.m.s. value. The size of these motors can be gauged from the photograph reproduced in Fig. 4 which shows them being tested in The English Electric Company's works.

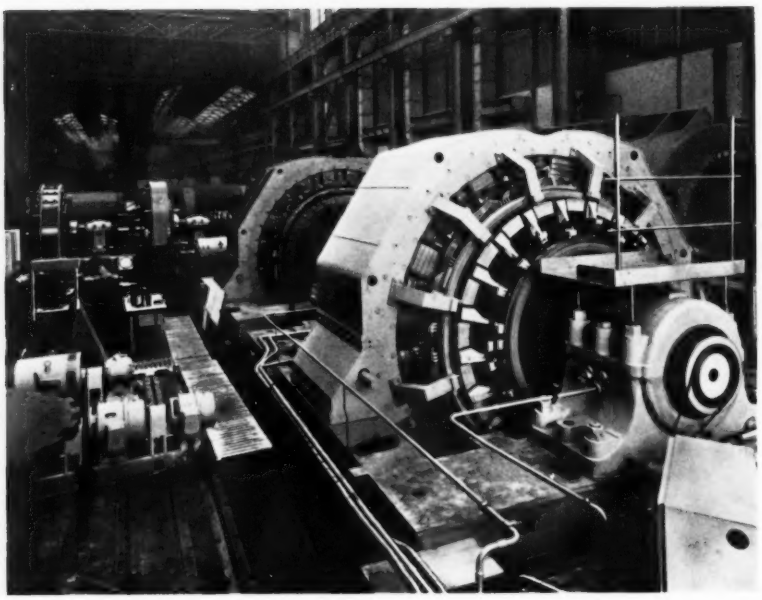


Fig. 4.—Motors for twin-drive slabbing mill, coupled together for tests after manufacture. These motors have a combined peak output of more than 30,000 h.p. but are controlled to reverse from base speed to base speed in one second

Despite their size their control equipment enables them to reverse from base speed to base speed in one second.

The rolling direction and speed of the mill is under the complete control of the mill driver, who sits in a pulpit overlooking the mill. The control scheme is arranged so that the mill responds faithfully to movements made by the driver on a controller, either hand operated or, more usually, foot operated.

The fast accurate response of the mill to the movements on this controller is obtained by the use of high-power-gain servo control of the voltage of the four Ward-Leonard generators needed to supply

GMA	Generator magnetic amplifier
GCE	Generator control exciter
GE	Generator main exciter
MMA	Motor magnetic amplifier
MCE	Motor control exciter
ME	Motor main exciter
TM	Top roll motor
BM	Bottom roll motor
TG	Generators for top roll motor
BG	Generators for bottom roll motor

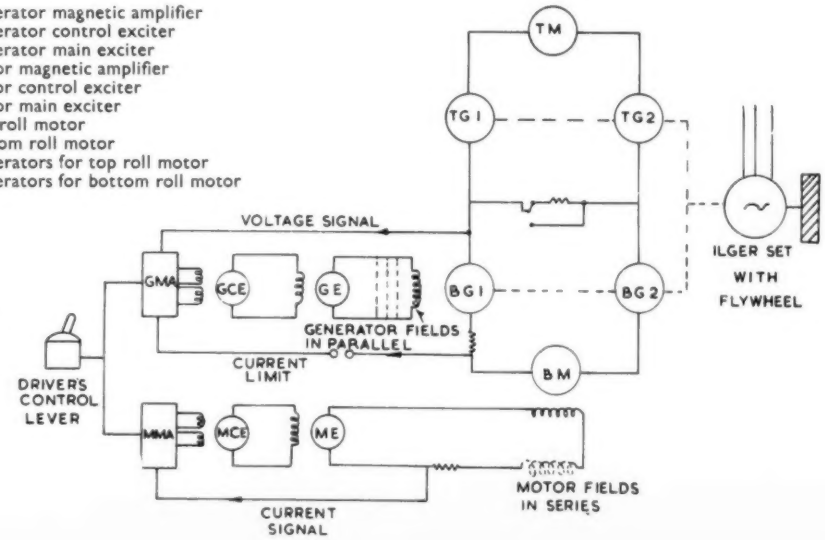


Fig. 5.—Reversing mill control

the two motors, and of the field current in the two motors. These controls are subject to over-riding current limit which allows the armature current to rise to within the safe working peak.

The essentials of the primary mill control are shown in the simplified diagram in Fig. 5. This control uses a combination of magnetic amplifiers, operating at 400 cycles per second to give high amplification and negligible time delay, and fast-response exciters. Three stages of amplification are used in order to provide the appreciable power required to excite the fields of the generators and motors and to give forcing voltages of several times the normal to overcome the time constants of these fields.

Although an amplifying control exciter has been used in this illustration, such a stage is not always necessary and the present tendency is to omit it.

The first movements of the foot controller from its centre (off) position cause increasing current in the reference winding of the generator magnetic amplifier GMA. The corresponding rise of generator voltage is fed back to the reset winding on the amplifier. This winding is connected to oppose the reference winding so that under steady-state conditions the net excitation is the small difference needed to maintain the generator excitation. On the instant of application of reference current to the amplifier no reset signal is available and so the amplifier develops full output, giving full excitation on the main generator exciter GE. The armature of GE provides a considerable forcing voltage to the fields of the four generators, causing the output voltage of these to rise rapidly to the point when the reset excitation on the magnetic amplifier almost balances the reference voltage. Movement of the foot controller through the centre position causes the reversal of the reference voltage, so that the generator volts are forced to zero and then to the required value in the reverse direction.

If the full forcing were applied to the generators, particularly with the mill on load, then the accelerating current might cause overloading of the motors. To prevent this, a voltage proportional to the armature current of the motors is detected across their compoles. When this voltage exceeds the voltage of a bias in the circuit the excess is applied to a further winding on the magnetic amplifier which opposes the reference. For the duration of the load the effective reference is reduced and overloading is prevented. Normally the current limit circuit is set to commence operation at $2\frac{1}{2}$ times full load current and to hold the speed down against full reference at 3 times full load current.

The motor field range is applied on further movement of the foot controller. In this case the reset signal is of motor field current, and any difference between this and the reference signal is amplified through the motor magnetic amplifier MMA, the motor control exciter MCE, and the main motor exciter ME.

The sequencing operation is arranged so that there can be no field weakening until base speed is reached, and no alteration of armature voltage is possible unless the mill motors are at full field. This ensures that the motor is at full field, so providing the maximum torque, during acceleration to and deceleration from base speed.

In order to assist the machines to commutate the high transient current changes inherent in a fast reversal scheme, the frames of the generators and motors are of laminated construction. When solid frames are used the effect of the solid yoke causes the flux to lag slightly behind the field ampere-turns. While sufficient forcing can be applied to the control system to render this of no consequence to the rate of response under most conditions, the interpole flux must also pass through the yoke, and any delay in following the armature ampere-turn changes makes commutation more difficult, since it is the interpole flux which is the criterion in aiding commutation.

On many mills a reversal time of 1·5—2·0 seconds is perfectly satisfactory, considering mechanical wear on the mill and the length of the rolling passes. Provision is made for adjusting the responses by means of an exciter voltage limit which operates in a manner identical to the current limit. A low setting of this exciter limit slows down the response by limiting the forcing voltage available. The controls for both the generator voltage and motor field are provided with this feature.

The motors and generators are connected in series, as shown in Fig. 5, with the generators interposed between the two motors to give the minimum voltage between any points in the circuit.

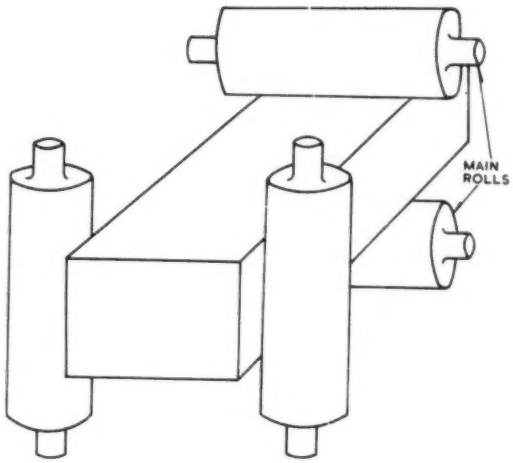


Fig. 6.—Arrangement of edger rolls

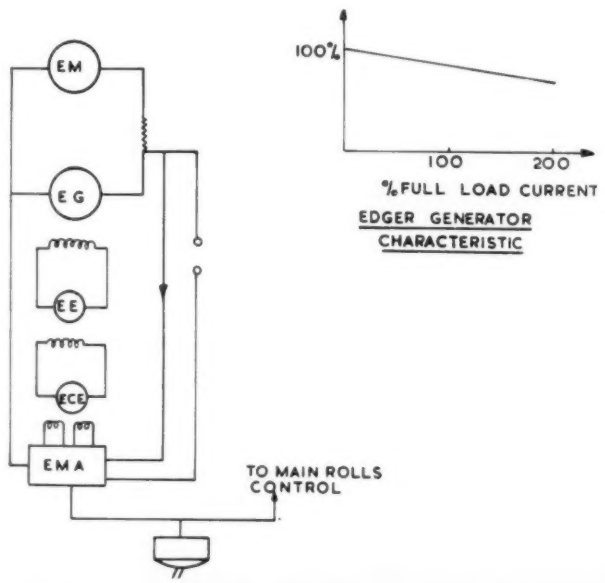
In order to provide torque and speed balance between the top and bottom rolls a connection is made as shown, using either what is called a mid-wire resistance or a solid mid-wire link. The effect of the resistance is to counter transient unbalanced currents, and also to provide an automatic correcting action for current and voltage differencies between the top and bottom loops. The higher the mid-wire resistance the better the load sharing.

On mills of this type there is a tendency for one motor (usually the bottom one) to take more current than the other on heavy drafts. The effect of this is to turn the metal either up or down, thus making handling difficult or damaging the rolls. To control the shape of the metal therefore it is often essential to provide a means of torque control of one roll relative to the other. This is done by modifying the voltages of the top and bottom generators according to a signal proportional to the difference between the loop currents, so that there is a tendency for a speed differential and hence a torque differential to be established. With the mid-wire resistance a large difference in generator voltage is necessary to achieve a speed differential. With the solid mid-wire, however, the adjustment of generator voltage is much more sensitive and effective but there is no inherent transient tendency for the loops to equalise. The choice of the link to use is left for the mill operators to make after satisfactory rolling has commenced.

Edging

To reduce the time required for tilting the slab for an edge-on pass, edger rolls are sometimes added before a primary mill as shown in Fig. 6. This not only increases the output tonnage (by reducing the number of passes required) but smooth edges are obtained and the edger rolls act as a scale breaker to remove scale and oxides from the side surfaces of the material.

Basically the edger control is very similar to that for the main drive, with an independent generator voltage control and a motor field control common with the motor field control of the main drive. However, since an edger is often coupled to the main mill through the hot material, a loose



EM Edger motor
EG Edger generator
EE Edger exciter
ECE Edger control exciter
EMA Edger magnetic amplifier

Fig. 7.—Dual control of edger and main rolls

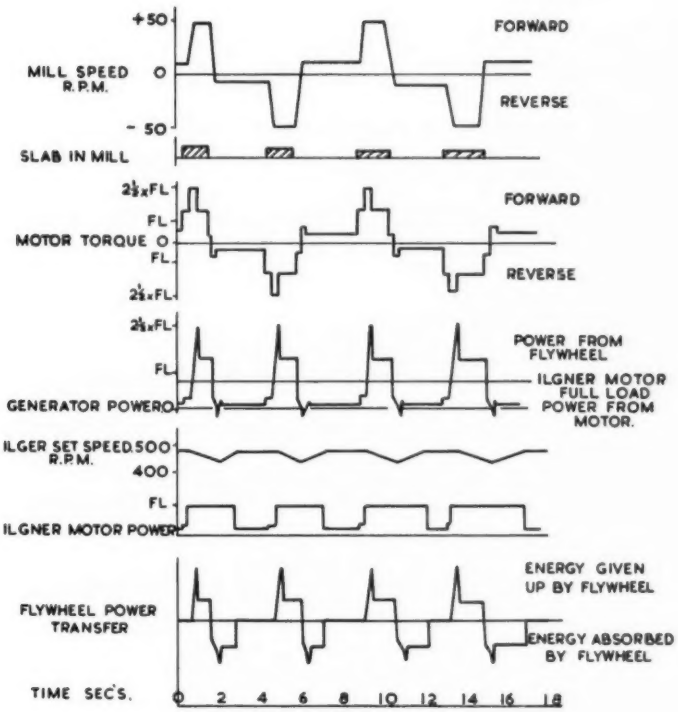


Fig. 8.—Power transfer in slabbing mill Ilgner set

speed tie is required between the two sets of rolls. The edger generator is therefore designed to have a 'soft' characteristic to allow its motor to follow the main mill irrespective of roll settings and drafts, as shown in Fig. 7.

If the power of the edger motor is sufficiently large, up to say 4000 h.p., fairly heavy reductions may be taken, but usually the power is less than this.

Primary Mill Ilgner Set

The use of Ilgner sets is by no means new on reversing mills ; it has in fact become traditional. It should however be mentioned as it is a system applied almost exclusively in steelworks for the main purpose of reducing the peaks imposed on the power system, so enabling the mill to operate from a smaller capacity distribution system. It also enables a somewhat smaller motor to drive the generators supplying the mill motor.

The Ilgner set comprises a generator or generators coupled to a flywheel and a driving motor of the slipring induction type having in its rotor circuit a slip regulator (i.e. a variable liquid resistance). The flywheel is designed to have a kinetic energy in horse-power-seconds, when running at the synchronous speed of the driving motor, of 20 to 50 times the horse-power of the driving motor. When heavy loads are applied to the set its speed is allowed to fall so that the flywheel gives up kinetic energy which is replaced when the load on the set is reduced.

Fig. 8 shows graphs of mill motor speed and torque, generator power, and Ilgner set speed and power for four of the passes on a typical reversing mill. Without the flywheel the induction motor's demand on the supply system would follow the generator power, rising to 2½ times full load. The use of the Ilgner set practically halves these peaks and can give a reduction of 30% or more in the r.m.s. rating of the induction motor.

Fig. 9 shows the control scheme used on the larger Ilgner sets. A current-transformer in the

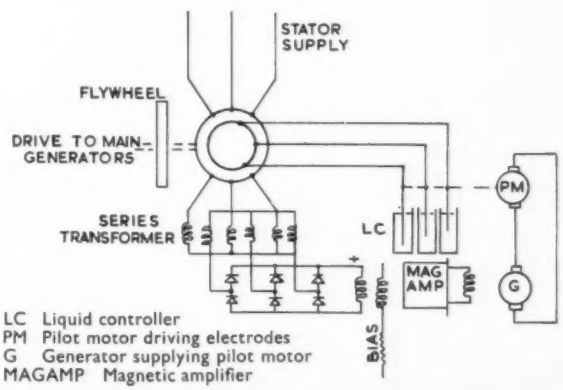


Fig. 9.—Basic scheme for Ilgner set control

stator circuit of the induction motor provides a signal of its load. When this rises above full load the magnetic amplifier, normally biased negative, receives a positive signal and its output causes the motor driving the slip-regulator blades to move and insert resistance into the motor rotor circuit, thus allowing the speed of the set to fall and the flywheel to give up its energy.

Rectifiers for Hot Reversing Mills

While the mercury-arc converter has found many applications on relatively constant-voltage duties, its use in the field of hot reversing mills has been severely limited by its lack of regenerative features. The first hot reversing mill in Britain fed by grid-controlled mercury-arc converters was therefore only commissioned as recently as December 1958.

In this description the term 'converter' is used rather than 'rectifier' to indicate that power is returned to as well as drawn from the supply. This is done by inversion, i.e. phasing the grids so that the converter can accept d.c. power from an outside source and return it to the a.c. line.

For reversing mill drives mercury-arc converters can be used instead of motor-generator sets in order to gain from the inherent advantages, the most important of which are :—

(*a*) Lower initial capital cost.

(*b*) Simpler foundations and lower civil engineering costs due to reduced weight and static nature.

(*c*) Crane capacity is often reduced.

(*d*) Reduction in energy costs due to the higher efficiency.

(*e*) Rapid control since there is no generator field forcing, and low power required for the control of the grids.

(*f*) Reduced maintenance and much quieter operation.

One of the many difficulties to be overcome is that a mercury-arc converter can pass direct current in one direction only. On reversing-mill duty considerable rotational kinetic energy has to be absorbed from the motor armature to reduce the speed quickly. This involves a reversal of armature current, and special arrangements have to be made to brake the motor economically.

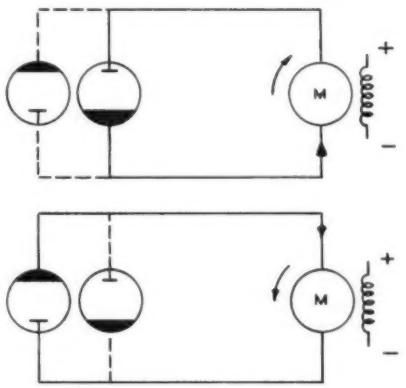


Fig. 10(a).—Back to back converters

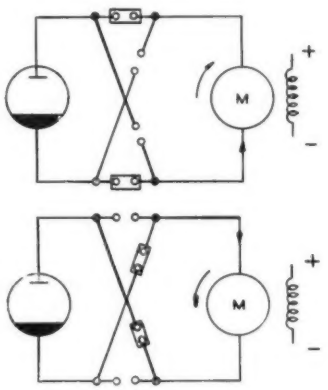


Fig. 10(b).—Converter with armature reversal

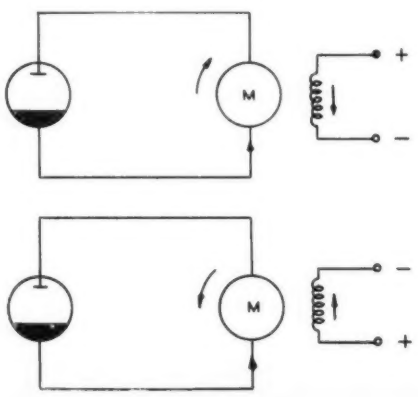


Fig. 10(c).—Converter with field reversal

Three methods can be used :—

(1) Back-to-back converters, two converters being connected in opposite polarity to each other as in Fig. 10(*a*). Each unit carries the current in its respective direction, the regenerative converter feeding power back into the supply system, i.e. inverting. This method is fast and smooth but expensive in initial outlay, and would normally be applied rather to cold tandem mills than hot reversing mills.

(2) One converter only, with an armature switch which on reversal changes the polarity of the motor with respect to the converter. This method is represented in Fig. 10(*b*). The heavy armature-circuit contactors required, operating several million times per year, may give cause for thought, but units are available which will adequately stand up to this duty without excessive maintenance.

(3) One converter only, with the motor current maintained in the same direction throughout, and the motor field reversed to permit braking, as shown in Fig. 10(*c*). The armature switch is avoided with this scheme, but the performance is slower (due to the delay in reversing the field) than in either of the previous methods. However, on all but the fastest mills this may be no disadvantage, a base to base reversal time of 2 seconds being easily achieved.

Operation with a converter scheme however causes harmonics to be fed into the supply system, and furthermore, since there is no cushioning effect between the supply and the load, repeated load changes are reflected almost directly into the mains and cause fluctuations in voltage. The solution to the former problem is to provide an adequate number of phases, but the matter of supply voltage variations is much more critical. A different method of grid-phasing may be used to reduce the reactive load peaks at low voltage, but usually it is necessary to study carefully the particular power supply system and the effects of the load imposed upon it, to ensure that an irritating level of fluctuation is precluded.

Primary Mill Auxiliaries

The great power, fast response, and rapid reversal time of the primary mill is of little consequence unless the time taken in delivering the ingot to the mill, handling it between passes, and finally delivering it to the slab yard is reduced to the minimum. Even with the fastest handling of the ingot and slab the period when the mill is actually rolling may be as low as 40% of the total time. Any avoidable delay in handling the ingot will reduce appreciably the output of the mill.

The auxiliaries associated with a slabbing mill normally include : the ingot buggy for conveying the ingot from the soaking pits, where it has been brought to the correct rolling temperature, to the mill tables ; the roller tables on either side of the mill which carry the ever increasing length of metal as it passes back and forth between the rolls in its transition from ingot to slab ; the manipulators which position the metal to enter the rolls correctly and which may turn it on its side for an edging pass ; the screwdowns which move the top roll up and down to give the required roll opening for each pass ; the runout tables which convey the slab to the shear and then on to the slab yard ; and the slab shear which crops the slab ready for the next rolling stage.

The original auxiliary drives used constant-voltage d.c. motors supplied from the works d.c. power system. Starting and crude speed control were effected by the use of series resistance short-circuited by contactors closing in sequence, with the lowest speed sometimes obtained by an armature divert resistance. Stopping would be by dynamic braking or plugging.

This system still finds many suitable applications but has largely been superseded for primary mill auxiliaries for the following reasons.

(*a*) The starting and reversing time is extended by delaying the closing of the starting contactors to prevent excessive over-loading with the heaviest mechanical load applied. This does not allow the fastest acceleration when the mechanical load is reduced.

(*b*) The wear and tear on the heavy contactors, opening and closing frequently with the full overload current of the motor, is appreciable.

(*c*) Since no regenerative braking is possible, considerable energy must be dissipated in large resistance units on starting and dynamic braking.

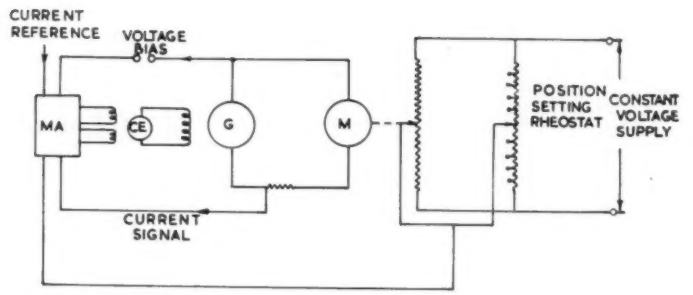


Fig. 11.—Over-riding position control for ingot car

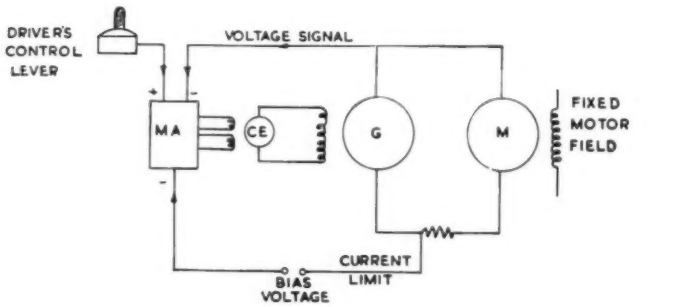


Fig. 12.—Part of Ward-Leonard control for screw-down drive

(*d*) Where accurate positioning is needed, the resistance-started constant-voltage motor lacks a stable low speed.

The closed loop Ward-Leonard system has none of these disadvantages and is particularly adaptable to the special requirements of controls on the ingot car, screwdowns and slab shears.

Ingot Car

The car which transports the ingot to the mill rolls may have to travel up to 1000 feet from its loading point at the soaking pits, which even at a maximum speed of 1000 f.p.m. takes over one minute. When operating from the pits furthest from the mill this could slow down production, especially on small ingots which are easily rolled. Shuttling arrangements must therefore take full advantage of modern controls to ensure maximum speed and minimum travel time over the distance, bearing in mind that the car with ingots may weigh over 120 tons.

Closed loop current control as shown in Fig. 11 provides tension in the winch-hauled ropes, while generator voltage limitation allows the maximum motor speed to be attained subject to an over-riding position control system which monitors the relative positions of the car and its terminal. The car can thus be positioned either at the mill or at any one of the pits selected by the operator from his production schedule. When the operator presses his ' run ' button the car accelerates to its maximum speed, the tension on the ropes is held steady by the current control, and by using the position device troublesome and often unreliable track switches can be eliminated. Special circuits prevent deceleration until the correct distance has been travelled, thus ensuring the optimum operating conditions compatible with safety.

Screwdowns

On many slabbing mills it is normal to turn the slab on its side and roll the sides to the correct width and squareness once or twice during the reduction. For this edging pass the rolls may have to lift some 60 inches and then return for the next pass which is perhaps 12 inches. The problem on the screwdown drive is therefore that of obtaining a very rapid acceleration and high speed for edging passes and yet be capable of accurate positioning. In short, the rolls may have to move at 10 inches per second and yet must be set for finishing passes to an accuracy of 1/16 inch or less.

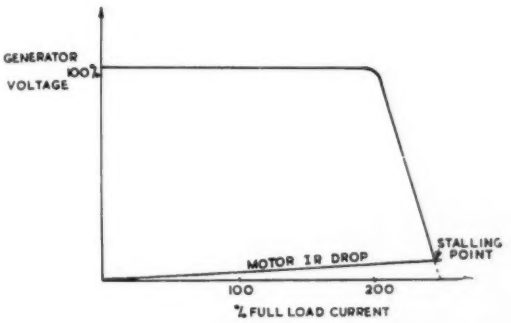


Fig. 13.—*Screwdown drive operating characteristic with current limit*

Part of a typical Ward-Leonard screwdown drive is shown in Fig. 12. The complete arrangement comprises two 200 h.p. mill type motors, specially constructed to stand up to the arduous steelworks duty, connected in series-sandwich with their respective generators. The latter, as on many auxiliary drives, are driven from different motor-generator sets so that in the event of failure on one machine continuity of operation can be maintained, if at a slower rate.

A 400 c/s magnetic amplifier and exciter are used for each generator voltage control, the voltage value being selected on a hand-operated controller by the pulpit operator, whose hands are available since he controls the mill reversals with his feet. As on the main drive control, the reference field is opposed by the generator voltage signal, the difference maintaining the output at the selected reference value. A current limit feature is provided, the signal of which is effective when the current rises above twice full load. If the current rises to $2\frac{1}{2}$ times full load, due to the operator holding his controller over under a heavy sustained load, e.g. a mechanical seizure, the current limit reduces the reference field down to a stall value. The operating characteristic is as shown in Fig. 13.

Normally on an auxiliary drive the inertia of the load relative to the motor capacity is much higher than on larger equipments, and so the current limit feature is usually the factor which determines the speed of response and the reversal times. One advantage of this type of control is that during speed changes the system is held in current limit effectively and efficiently, thus providing for optimum operating conditions. The high-frequency magnetic amplifiers allow a fast response, but more important with the advent of truly automatic working, their low power input requirements are a great advantage.

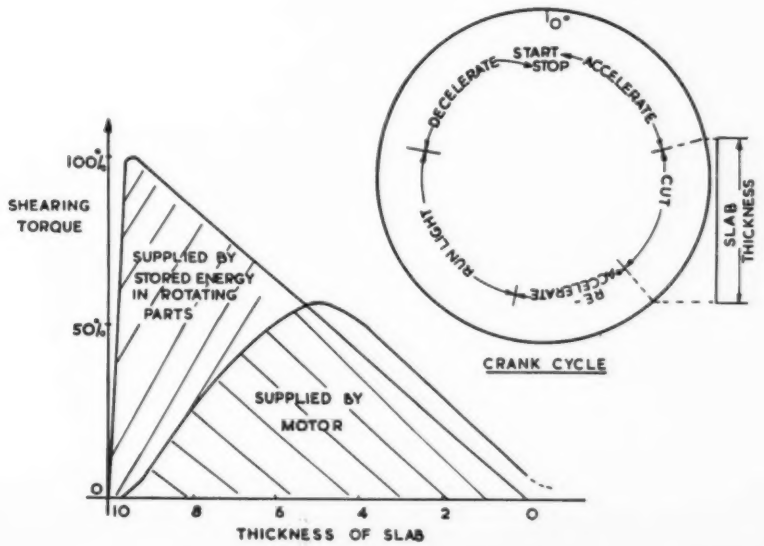


Fig. 14.—*Cutting cycle for slab shear*

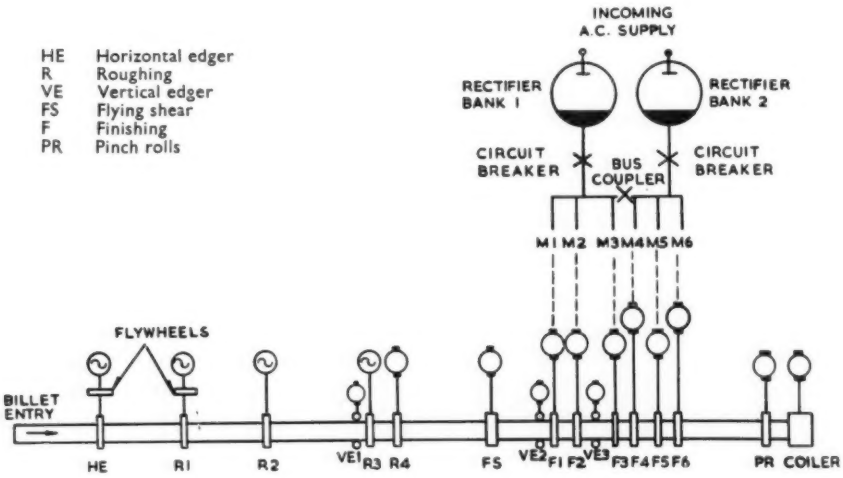


Fig. 15. Schematic diagram of hot strip mill, showing rectifier busbar arrangement

Slab Shear

When the slab has been finally rolled and passed over the runout tables it has to be cut up into 6 ft—10 ft lengths to facilitate further handling. The cross-section of the material may be up to 60 in x 10 in, i.e. 600 square inches, and the shear has to accelerate, cut and brake in a cycle time that will keep up with the mill. The cutting cycle for such a unit is shown in Fig. 14.

Ward-Leonard control similar to that previously described for the screwdown drive is used, but due to the extremely high peak cutting torque which may be required at the shear crank, some assistance is required from the kinetic energy of the moving parts if a motor of reasonable size and cost is desired. Thus enough droop is built into the Ward-Leonard loop to allow the motor and the rotating parts of the shear to give up their energy during the cut.

From here the slabs are reheated before passing to the next stages of reduction.

HOT CONTINUOUS MILLS

Hot continuous mills further reduce the slabs or blooms received from the primary mills. The finished product may be coiled or flat sheets, or rods and bars either in coiled or straight form, of varying thicknesses and diameters. Although much of this output is sold as a finished product, large quantities are passed on to additional processes for further treatment. In this stage of reduction, as before, there is a drive towards improvement in the quality and tolerance of the product and in the flexibility of rolling.

Hot Strip Mill

The arrangement of a typical modern hot strip mill is shown in Fig. 15. In this case there are four horizontal roughing stands and six finishing stands which normally reduce slabs approximately 3 in. thick and 16 in. wide to coiled sheet ·064 in. thick.

This particular example is a narrow high-speed strip mill which can roll the narrowest widths down to a thickness of ·048 in. On wider strip mills the control system is exactly the same but of course larger horse-powers are required to reduce the extra width and mass of material.

Each stand is individually driven and the horse-powers of the drives are tabulated below.

STAND	H.P.	SPEED	TYPE OF MOTOR
R1	700	490	A.C. slipring induction
R2	1200	428	A.C. synchronous
R3	,,	,,	,,
R4	1200	425—850	Individual D.C.
F1	1200	425—850	,,
F2	1750	357—760	,,
F3	,,	,,	,,
F4	,,	,,	,,
F5	,,	,,	,,
F6	1200	425—925	,,

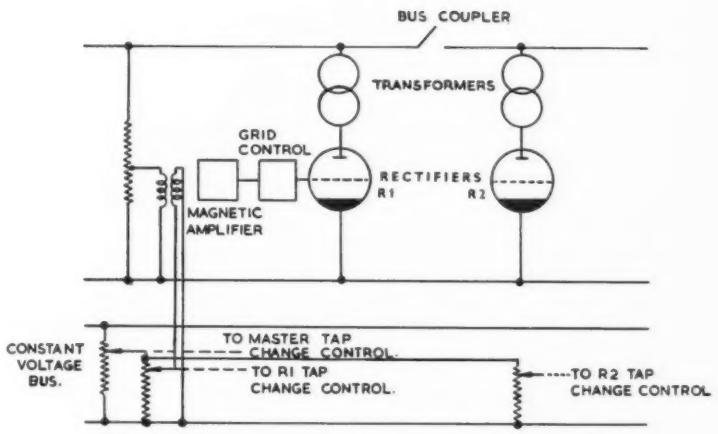


Fig. 16.
Rectifier voltage control

In this example the final speed is up to 3000 f.p.m., and special problems arise due to the fact that there is a variation in speed as the material enters and leaves the rolls of each stand. Since the material is simultaneously reduced in several stands, the roll speeds have to be controlled to within close tolerances, as small inaccuracies may be sufficient to produce interstand tension or stretching, with consequent deformation of the material. Similarly, loops must not be allowed to form lest they build up, fall over and cause a double-thickness entry, which will not only damage the mill rolls but cause the material following to pile up. Good rolling is obtained without tension.

Unlike a cold mill, which accelerates with the material in the mill from almost zero speed, a hot continuous mill is run at a fixed speed, and entry is with the stands running at this speed. Thus there must be good control of stand speed, interstand looping and quick recovery after the initial impact drop, and the setting-up procedure for the mill must be simple and flexible so that rolling programmes may be changed quickly, simply and confidently. Furthermore, during actual rolling the stands should be capable of being adjusted to trim the speeds for any variation in slab temperature and stretch in the mill housings.

The control of the roughing stands is straightforward, since the strip is travelling slowly. It is thick and strong and there is a considerable distance between the stands, so that the piece leaves one stand before it enters the next. Since stands R3 and R4 are close together, R4 has a d.c. drive which can vary in speed to match the speed of R3 which only varies according to the roll diameter since it is a constant-speed machine. The speed of R4 can also vary according to the draft taken on R3, so that the ability to adjust its speed gives greater flexibility in rolling.

For the finishing train however, higher rolling speeds require additional control, and two systems are used.

(1) Grid controlled mercury-arc rectifiers connected in parallel banks supply the main busbar system for the motor armatures. The voltage of this supply is adjustable over the range 360-600 volts and is held constant against changes in load or supply voltage by a magnetic amplifier control on the grids of the rectifiers.

(2) Speed control of the individual motors is applied through the mill motor fields in order to obtain both accuracy and a fast transient response.

The motor speeds are in fact held to within $\frac{1}{4}\%$ of the pre-set speed.

A further feature is provided which takes up the slack during rolling and also trims the stand speed settings to correct any initial setting-up errors of the operators.

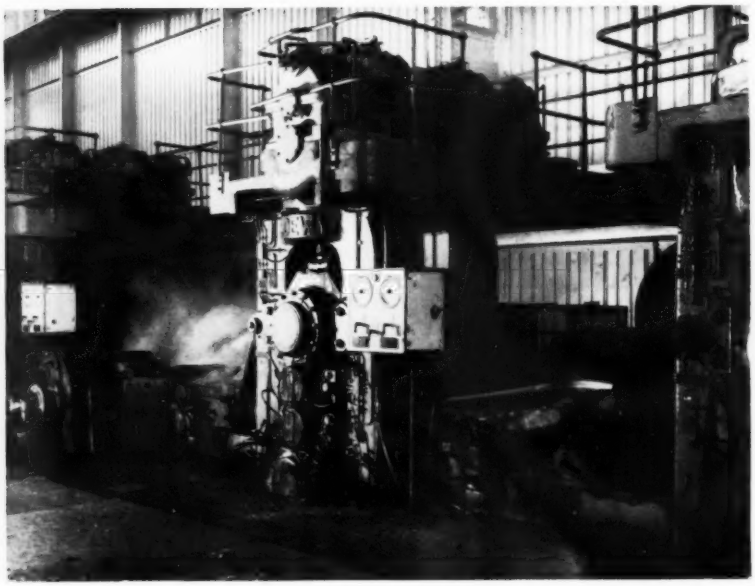


Fig. 17.—Finishing stands of continuous hot strip mill, showing the strip passing over the loop-lifter table

The busbar arrangement, also shown in Fig. 15, permits three modes of operation :—

(i) The normal method of ' split-bus ' in which each section is set up and controlled independently.

(ii) With the bus-coupler closed and the operating conditions thus ' common-bus.' This not only raises the fault capacity of the system considerably but precludes the wide variety of speed cones available with (i). Circuits are provided to ensure that the rectifier banks share the load equally.

(iii) For light loading, the ' common-bus ' system (ii) can be used but with only one rectifier bank energised.

The rectifier voltage control is shown diagrammatically in Fig. 16. This consists of a magnetic amplifier which feeds the control grids of the mercury-arc rectifier. The reference winding of the magnetic amplifier is fed from the reference rheostats which determine the output voltage of the rectifiers. A signal proportional to this output is backed off against the reference, and the difference provides the correct excitation for the selected output. In this way the voltage is set, and so long as the reference is not changed the output voltage will be held constant. When a load is applied the voltage tends to drop, and the increased error increases the output of the magnetic amplifier until a balance is again reached when the rectifier voltage is at its previously set value. The range of voltage is 360-600 with any of the three busbar arrangements previously mentioned. In order to maintain a good power factor the reference

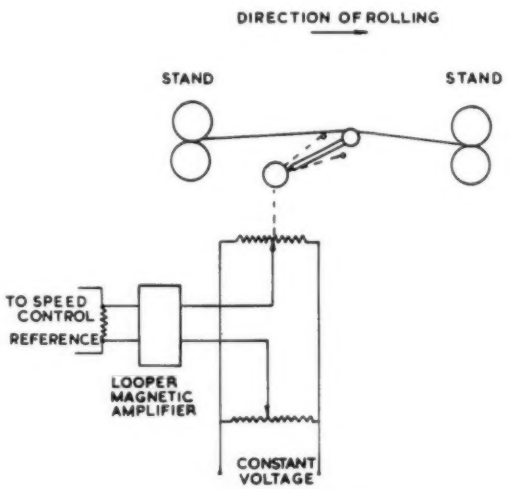


Fig. 18.—Loop lifter control

rheostat tracks are ganged to other tracks of the same rheostats which can initiate an on-load tap-changer movement. The control thus ensures that too much grid control is not applied over the working range. When the motor room operator is told of a light rolling programme he can manually adjust the tap-changer voltage relative to the voltage control which, although remaining at a constant value will, due to the lower a.c. supply volts, result in higher operating power factor.

In a similar manner a closed-loop speed control operates on each motor to maintain its speed constant at the pre-set value which can be adjusted by the mill operator. To help to set up the mill and to maintain the correct rolling condition, automatic loop lifters are included. The control associated with this feature is as shown in Fig. 18. The loop lifter arm, which is held in contact with the strip, drives the arm of the position rheostat, and any difference in speed between adjacent stands causes a slow increase or decrease in the length of the strip. This causes the looper arm to move and displace the position rheostat, and the resulting error signal is amplified through a magnetic amplifier which trims the speed of the preceding stand both transiently and by a follow-up control. A master stand is chosen and adjustment is made both forwards and backwards from this.

The material is coiled on hot mandrel-type coilers which ensure tight well-built coils. As the strip enters the coiler, guide rolls hold the first few turns and the mandrel is expanded, thus gripping the coil. The coil then builds up under tension developed between the coiler motor and the last finishing stand. When the strip leaves the last stand, pinch rolls close to act as a drag generator, thus maintaining the coiling tension.

Rod and Bar Mills

With this type of mill the question of looping and stretching is very much more important due to the smaller sections being rolled and the greater accuracy required in the finished product.

Some idea of the length of time available for correcting the speed can be gained from the following figures :—

Rolling speed = 3000 f.p.m. = 50 f.p.s.
Distance between stands = 15 feet
A speed difference of 1% = ·5 f.p.s.

Thus an error of 1% in speed, if it persists for 1 second, would give rise to an increase in length of 6 inches in 15 feet, which is illustrated to scale in Fig. 19.

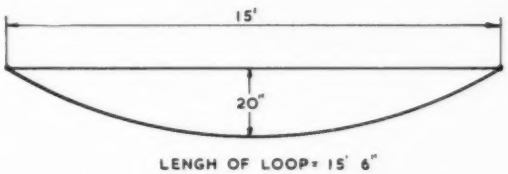


Fig. 19.—Effect of increase in rod length

A typical impact drop, i.e. the variation in speed caused by the sudden application of load, is shown in Fig. 20. The shaded areas show the amount of stretch and loop respectively which the material

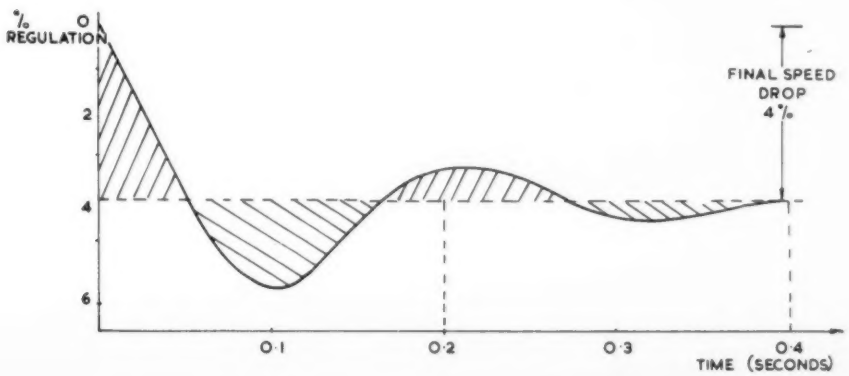
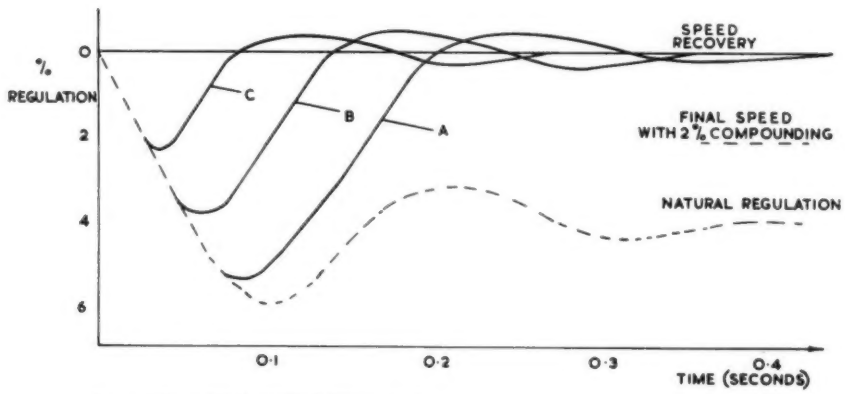


Fig. 20.—Typical impact drop of normal-regulation machine



A Inherently low-regulation motors
B Motors with some form of speed control
C Individual stand speed control

Fig. 21.—Impact drops with added control

would undergo during this transient step. The final level achieved after approximately half a second is shown dotted. It is obvious that the lower the speed drop the better things would be, but unfortunately such improvement increases the cost considerably and so several different methods are used.

A. Inherently low-regulation machines which give a simple and easily adjusted control, all fed from a common d.c. busbar.

B. Some form of speed control applied to the motors concerned, either by

(i) armature voltage control via a booster, with the motors fed from a common d.c. busbar, or

(ii) motor field control with the motors again fed from a common d.c. parallel supply system.

C. Individual stand speed control where each motor is fed and controlled through either a rectifier or d.c. generator.

Specimen impact drops for the above conditions are illustrated in Fig. 21, with the basic curve of Fig. 20 superimposed. It will be noticed that the individual control gives the fastest recovery time. However, using a combination of motor field control and compounding (i.e. a signal which reduces the speed according to the armature current) the areas of loop and stretch can be kept within permissible limits.

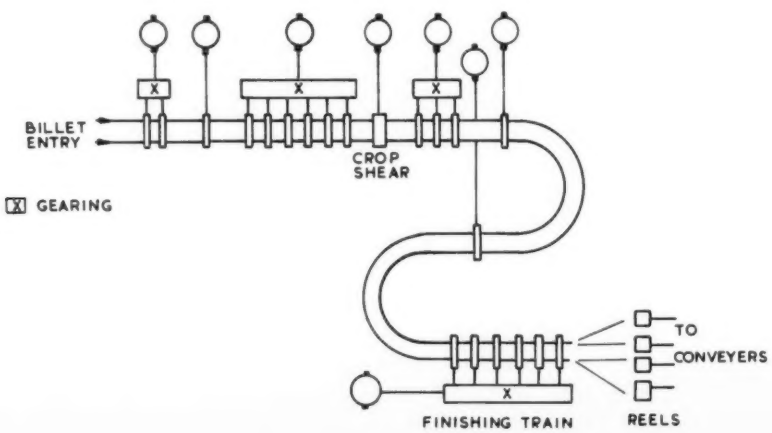


Fig. 22.—Schematic diagram of two-strand rod mill

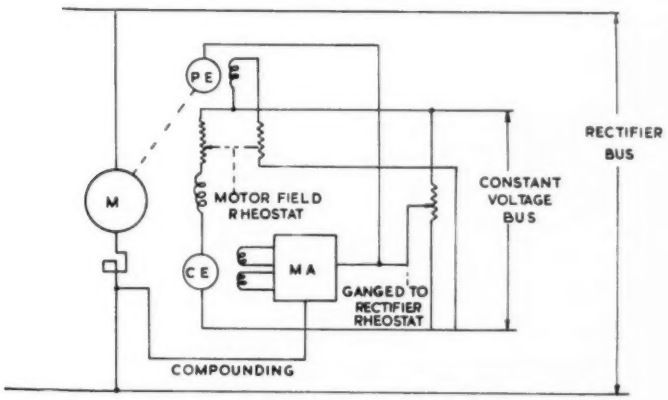


Fig. 23.—Basic stand speed control circuit

The arrangement of a typical two-strand rod mill is shown in Fig. 22. Here, billets 30 ft x $2\frac{1}{2}$ in x $2\frac{1}{2}$ in are fed from the furnace into the appropriate strand guides, and the material or stock is reduced in successive stands down to a final size of $\frac{1}{4}$ inch diameter round section. Other sections such as squares and hexagonals are usually rolled on single strand mills due to the rather more complex rolling arrangements.

This mill has seven main drives, several of them driving two or more stands. The material from Stand 20 (the final stand) is coiled in any of the four reels at an exit speed of up to 6000 f.p.m. The main drive motors, which are shunt wound, separately excited, adjustable speed d.c. machines, are supplied from a rectifier busbar which is capable of operation over the range 450-600 volts. The horse-powers and speeds of these motors are:—

MOTOR	STAND	H.P.	SPEED
1	1—2	300	250—750
2	3	300	250—750
3	4—9	1250	250—625
4	10—12	800	200—500
5	13	350	250—600
6	14	350	300—675
7	15—20	1500	575—980

The rectifier voltage control used is identical to that already described on the hot strip mill although, since only one busbar is required due to the lower total horse-power involved, no changeover and load sharing arrangements are necessary. Although the last motor drives six stands (i.e. 15 to 20), individual stand drives are occasionally used on the finishing stands where the interstand distance is small, the rolling speed high and the reductions large, thereby necessitating careful individual adjustment to compensate for roll diameter errors and large impact drops. This adjustment is naturally not possible when the stands are geared together.

The accuracy required for a drive of this kind (operating up to 6000 f.p.m.) is obtained by applying an automatic speed control through each motor field by means of laminated-frame control exciters in series with each field. The basic speed control circuit is shown in Fig. 23.

The voltage from the pilot exciter, which is proportional to the motor speed, is backed off against a set speed-reference voltage, the difference being amplified through a magnetic amplifier on to the field of the series exciter, which bucks or boosts the field voltage in such a way as to correct the speed via the motor field current for any variations. Under steady conditions the pilot exciter voltage equals the reference voltage, and the field exciter gives no output. However, under transient loading conditions, i.e. when metal enters the rolls, the speed of the motor tends to fall. The consequent reduced pilot exciter voltage causes a current to flow in the magnetic amplifier control winding which makes the series exciter buck the field supply voltage, thus reducing the field current so that the motor returns to its former speed.

In addition to transient speed correction, any variation due to the heating up of the motor field, or armature reaction effects, which might cause speed drift, are taken into account. The speed control has an accuracy of $\frac{1}{4}\%$, and in order to obtain fast response 400 c/s magnetic amplifiers are used. Compounding or ' hard-soft ' control can be added by subtracting a signal proportional to load current, in which case the final speed is determined

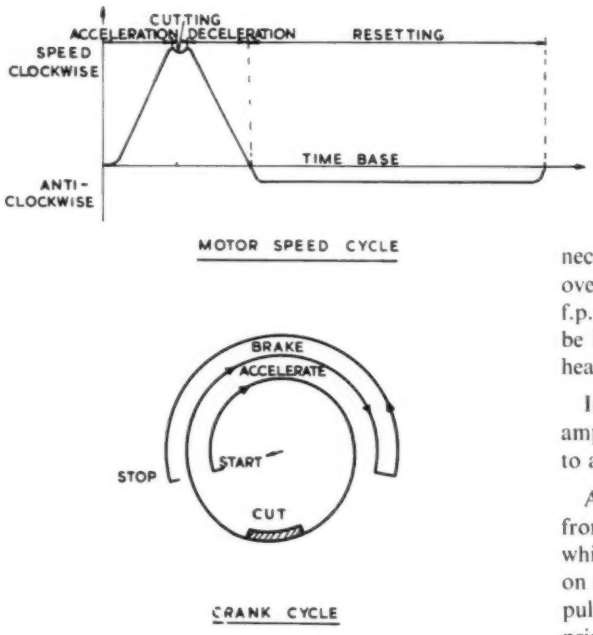


Fig. 24.—Flying shear duty cycle

by the motor load current. This is normally used with single-strand rolling, since if there is more than one strand then the speed of the stand, which may already have metal in the rolls, would be changed by the applied load of the second strand.

Flying Shear

On certain mills of this type the material, instead of being coiled up or reeled, is cut into straight lengths according to the particular programme being rolled. The stock is run out of one of the intermediate stands at rolling speed and cut into lengths by a 'flying shear' as it is called, placed just beyond the chosen stand. The material is therefore cut while travelling at speeds of up to 2300 f.p.m., and this provides an interesting example of high-speed high-accuracy automatic control.

The particular shear in the mill under consideration is of the stop-start variety and special features are required in the electrical equipment to meet the duty shown in Fig. 24.

The shear consists of two blades, geared together and driven by a 75 h.p. 230 volt standard mill-type motor supplied from a separate motor-generator set. The blades are accelerated to cutting speed, cut, decelerate and then reset to rest for the next operation. For the $\frac{1}{4}$ inch diameter rod the permissible time is 0·3 second to accelerate to 2300 f.p.m. blade speed.

Thus a low inertia drive is obviously necessary and yet, since the shear will be cutting over a wide range of speeds down to about 900 f.p.m. on heavier sections, enough inertia has to be built into the drive to carry out effectively the heavy low-speed cut.

In the control scheme a combination of magnetic amplifiers and quick-acting control exciters is used to achieve this performance.

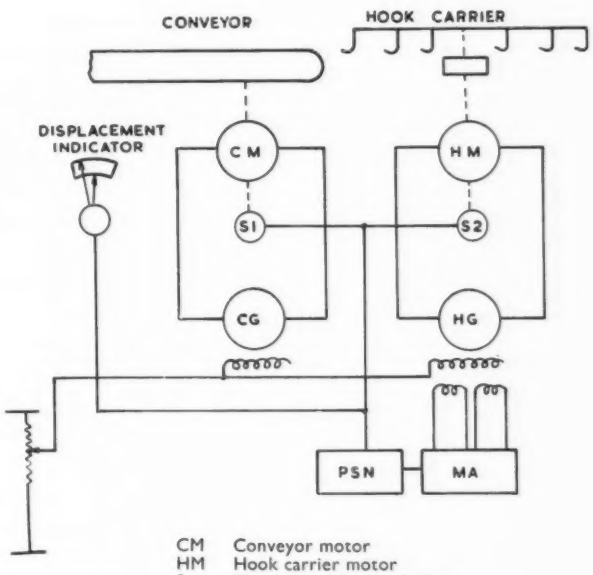
As the hot bar passes under the shear a signal from a photo-cell mounted on the shear housing, which detects the nose of the hot material, is put on to a magnetic disc length-measuring device via a pulse head. The disc is a memory device using the principle of magnetic storage. After the pulse has travelled a distance corresponding to the set cut length, it operates a relay which releases the shear brake and then, after a short interval to complete the release, operates another relay which applies a reference voltage, proportional to bar speed, to the magnetic amplifier. The contactor circuits are arranged to release the generator 'suicide' at the appropriate time. The shear motor accelerates under current limit to the strip speed, which must be attained before the blades cut the bar. This means acceleration from rest to full speed in approximately 2/3 of a shear revolution (0·3 second). Thus high-speed relays are used wherever possible.

At the instant of cutting, another pulse, this time from a limit switch geared to the shear blades, is put on to the magnetic disc. At the same time the reference voltage is switched off by another cam of the limit switch, and the shear decelerates with the assistance of a small negative reference voltage which is also applied. As the shear motor comes to rest the action of the negative reference voltage reverses the shear so that it inches in the reverse direction to take up its correct starting position. The limit switch operates the brakes and 'suicide,' and the shear stops in the reset zone.

Further cuts are initiated by the magnetic disc pulses which after the first cut always come from the shear limit switch. This high-speed rotary type limit switch, which is directly coupled to the shear crank, consists of a series of discs splined on to a shaft, each disc having conducting and non-conducting sectors. Brushes pick up the signal as the rotation of the disc effects contact. This provides a robust, accurate, high performance method of detecting blade position.

Since the peripheral speed of the switch is high, the relays which operate from it are also high-speed, operating in less than 10 milliseconds.

Thus a combination of relays, switches, photoelectric cells and magnetic amplifiers is used for effectively linking the many devices used today in automatic control in order to meet the special requirements of the drive.



CM Conveyor motor
HM Hook carrier motor
S Magslip positioning devices
CG Conveyor generator
HG Hook carrier generator
PSN Phase sensing network
MA Magnetic amplifier

Fig. 25.—Conveyor position control

Conveyor and Hook Carrier

When the outlet from the last stand is used the material, as already mentioned, is wound into coils, and these are moved to the storage area of the mill via a conveyor and hook carrier system consisting of several sections. In order to prevent damage to the coils as they are transferred between sections, a control is applied to maintain the position of the hook carrier relative to the main conveyor. This is done by means of magslip positioning devices on each of the drives, so arranged that any displacement trims a field on one of the supply generators so that the correct relative positions are re-established. The control scheme is shown in Fig. 25. Indication of synchronism or departure therefrom is given to the pulpit operator by an instrument which detects the out-of-phase signal. Since such departures will normally be only fractions of an inch, no external adjustment is required. This control naturally operates principally under accelerating and decelerating conditions when displacement is most likely to occur.

This article will be concluded by Part II, to be published in the December 1959 issue of this journal, volume sixteen, number four.

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